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Risk of fire emergency evacuation in complex construction sites: Integration of 4D-BIM, social force modeling, and fire quantitative risk assessment

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ABSTRACT

Construction industry is claimed to be the fourth most dangerous sector by number of fatalities. In complex construction sites, emergency evacuation risk assessment is a challenging task due to their ever-changing nature. This study developed a model to analyze the risk of fire emergency occurrence, and risks which are associated with evacuation performance (in response to that emergency) through an integrated approach in complex construction sites. To analyze the evacuation scenarios more realistically, we utilized Social Force Model (SFM) simulation engine. Using SFM for simulating the evacuation of complex construction sites has not been adequately addressed in the literature. Microscopically simulating the evacuation scenarios for all workdays of the studied complex project required high computation efforts. To tackle this computation challenge, a parallel computing technique was coupled with SFM simulation engine. More importantly, in this paper site's evacuation performance was evaluated multi-objectively considering evacuation time and evacuation safety. The construction site's emergency scenarios were modeled by 4D-BIM, potential for trigger fire emergency was determined by a fire ignition Quantitative Risk Assessment (QRA) module, and site evacuation was simulated by SFM simulation engine. The proposed framework handled the collaboration of 4D-BIM, fire QRA module, and SFM engine. This research study benefited from data driven from a real mega project. The findings demonstrated that analyzing the risk of evacuation through an integrated approach by the proposed model could render more realistic results. The results also provided the project managers with a reliable safety decision-making support.

1. Introduction

Arranging a construction site is basically a multi-objective task. Determining the safety conditions of such complex environments has long been a challenging issue for project managers. Efficient emergency evacuation is one of the most important primitive responses to a probable fire emergency situation. The process of evacuation, however, highly depends on the real-time conditions of the site which need to be determined dynamically. Generally, construction sites are prone to a wide range of hazards due to uncertain extreme events and the ever-changing nature of such environments [1]. This issue is also supported by the fact that construction is claimed to be the fourth most dangerous industry by the number of fatalities [2] where around five thousand fire accidents occur per year, only in the United States [3]. Accordingly, it is very rare to finish a large-scale project without any accident [1]. Thus, construction managers must minimize safety risks, as well as have an efficient response plan for probable emergencies. This is a challenging task in the cases of complex and large-scale construction projects where safety analysis requires significant efforts. Real-time evacuation risk assessment of such complex environments is a time-consuming and labor-intensive task, and manual analyze of daily-changing evacuation scenarios in a microscopic manner is not easy-to-conduct in a practical time. Although wide variety of studies have been devoted to the evacuation of public facilities such as mega-malls, stadiums, and transportation terminals and stations [4,5], little has been done on the risky environments such as construction sites where physical scene, escape routes, and occupancy conditions change from day to day [6].

In the literature of safety management of construction sites, evacuation risk mostly refers to the risks which are associated with evacuation performance (such as evacuation time). However, analyzing the risk of occurrence of a fire emergency, and risks which are associated with the evacuation performance (as a response to that emergency) through an integrated approach could render more reliable results. With this objective in mine, a work zone with high evacuation capability should not be considered as a low-risk zone if there is a high potential for fire. On the contrary, a work zone with minor accident potential should be

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highly attended if its evacuation is difficult. Thus, concurrent consideration of these two metrics (potential for fire emergency occurrence, and evacuation capability in response to that emergency) could reflect the overall evacuation risk more reliably. One of the contributions of this study to the body of safety knowledge is demonstrating the efficiency and reliability of this approach in the risk assessment of evacuation of construction sites. This study developed a model to analyze the risk of fire emergency occurrence, and risk of safe evacuation performance (in response to that emergency) through an integrated approach in complex construction sites. To analyze the evacuation scenarios more realistically, we utilized Social Force Model (SFM) which is a microscopic simulation algorithm. The construction site's emergency scenarios were modeled by 4D Building Information Modeling (BIM), potential for trigger fire emergency was determined by a fire ignition Quantitative Risk Assessment (QRA) module, and site evacuation was simulated by SFM simulation engine. The proposed framework, however, handled the collaboration of 4D-BIM, fire QRA module, and SFM engine.

In addition, in most of the evacuation studies evacuation performance is evaluated only by measuring the evacuation time [7], while the new approach of evacuation studies considers safety of evacuation in addition to its quickness [8]. However, one of the most important factors in evacuation safety is the congestion level [8]. In this paper, Total Evacuation Time (TET) and congestion level are two metrics to evaluate evacuation performance. Besides, it can be extremely labor-intensive to manually analyze the above-mentioned risks for every part of a large-scale construction site on a daily basis. Therefore, the proposed framework could be much more effective in such construction projects due to providing high level of automation and its ability to cover probable changes in project schedule. In the context of this study, two additional objectives were achieved. First, during the literature review it was noted that there is an uncertainty in many cases of evacuation of construction sites. This uncertainty exists because some of the workers do not precisely follow many of the emergency instructions during the evacuation process [2,9]. A module was designed in this study to take such behaviors in the evacuation simulation. Second, utilizing SFM for simulating the evacuation of complex construction sites is not adequately addressed in the literature. Microscopically simulating the evacuation scenarios for all workdays in a complex project requires high computation efforts [10,11]. To tackle this computation challenge, a parallel computing technique was coupled with SFM simulation engine. Finally, the model was implemented on a real mega project.

The rest of the paper is organized as follows: section two presents a systematic literature review of the topic; section three addresses the methodology that is used to accomplish this study; section four describes the proposed model and the case study, and finally, the results are discussed in section five.

2. Related works

Experimental study on emergency evacuation in the presence of real threats is basically prohibited [12]. Therefore, researchers usually model the emergency evacuations. These models were initially developed through static approaches (such as Smith [13] and Sheffi, et al. [14]). With the static approach, movement of an individual is often simulated through equations considering constant walking speed and traveled distance between two nodes [13]. In two last decades, dynamic models were proposed which are able to duplicate the dynamic maneuvering of individuals as well as their dynamic surrounding environment [15] (such as Helbing and Molnar [16] and Turner and Penn [17]). In dynamic models, generally real-time situation of a moving individual is analyzed considering 'time' parameter [15,16]. Dynamic models are divided into microscopic models, and macroscopic models. Microscopic models take local interactions of pedestrians and their immediate environment into consideration while macroscopic models duplicate crowd behavior as a whole and ignore local pedestrian's dynamics [18]. Among the microscopic techniques (such as Cellular Automata (CA) [19], SFM [16], and Agent-Based Model (ABM) [17]) SFM has received more attention because of its ability to simulate individuals' socio-psychological and physical attributes [20,21]. These models also enabled the researchers to consider a wider range of facility environments, where they were almost impossible to be simulated with static models [22]. Consequently, an opportunity was provided for simulation of construction project sites as complex environments.

In the following, the literature on evacuation of complex environments, including construction sites, is reviewed. Table 1 summarizes the related works that have been devoted to evacuation of complex environments including construction sites. In this table, each study is subjected to a brief analysis with respect to the case study, simulation platform, research approach, and information platform.

In short, the following items can be perceived from Table 1:

- BIM is mostly utilized as the source of information for the mentioned studies.
- Route advising and evacuation evaluation are two of the most considered issues.
- 4D-BIM is employed most often in recent studies.
- Various versions of ABM are mostly used in emergency evacuation modeling.
- Large-scale buildings are the most studied cases in reviewed papers.
- Using virtual environment techniques is not sufficiently addressed in the studies with case study of construction sites.
- SFM has not been adequately utilized for simulating evacuation of complex environments particularly in construction sites where the site's layout can be dynamic.

The limited number of works on evacuation of construction project sites are reported in Table 1. Frantzich [6] developed a model to determine possibility of evacuation from a particular work zone to a safer location in a tunnel construction project in case of fire. A sensitivity analysis was performed in order to monitor the factors related to fire and evacuation capability. Frantzich [6] also observed that a rapid change in smoke propagation may have a significant effect on the evacuation process. Said, et al. [24] proposed an Agent-Based framework for determining evacuation time of persons working in high-rise construction sites. Labor evacuation was modeled in two levels: i) strategic wayfinding, and ii) discrete-time maneuvering in individual areas. In a more recent study, El Meouche, et al. [32] developed a model to find the least-risky evacuation paths in construction sites. They use Dijkstra's path finding algorithm to get the shortest path for evacuees to safely go from any position on the site to safe places. They also found that the best evacuation path is not necessarily the shortest one, but one that is also safe to traverse. A framework able to model complex construction sites was also recommended as a potential of research. Marzouk and Al Daour [22] presented a framework for planning labors emergency evacuation in construction sites. They provided a platform to integrate BIM and a simulation engine. Their results highlighted the importance of consideration of congestion during the evacuation process. Moreover, they revealed the influence of activity sequence on the overall evacuation time. Recently, Kim and Lee [34] proposed a framework to automatically analyze egress routes for various work crews using 4D-BIM, considering different work packages in a particular day of the project schedule. In their research study, total traveled distance was picked as the only path-finding objective. In the context of labors' behavior during evacuation, there was lack of an experimental study. Filling this research gap, Galea, et al. [2] recently captured a wide range of labors' behaviors during evacuation of construction project sites.

As discussed before, efficient simulation techniques have enabled researchers to model the evacuation of complex environments such as large-scale construction sites. Furthermore, 4D-BIM has emerged to feasible accurate modelling of complex environments on a timely basis [35]. 4D-BIM has been employed for a wide range of purposes in the field of construction, from design phase applications (such as Kim and

Teizer [36]) to construction monitoring purposes (such as Bosché [37]). However, a primary use of this utility in the Architecture, Engineering, and Construction (AEC) industry is safety management [38]. Rüppel and Schatz [23] presented new serious gaming based on a BIM platform to investigate the effect of facility condition on pedestrians' behavior in the event of emergency evacuation. Wang, et al. [25] investigated evacuation simulation of a large building based on Discrete Event Systems Specification (DEVS) for BIM authoring tools. The idea was to create a platform to extract building information to facilitate the simulation environment. An emergency evacuation was simulated by the ABM technique including the following behaviors. They took advantage of integrating 3D-GIS and BIM to establish a facility information structure. The Fire Dynamics Simulator (FDS) software package was then employed to simulate fire situations. The incorporation of 3D-GIS, BIM, and evacuation simulation engine was also claimed to enhance modelling of emergency responses. Li, et al. [26] developed a model to optimize localization of people in a building, equipped with a number of sensors, in the event of fire emergency. The multi-objective problem in this study was then solved by consideration of (i) improving room-level localization accuracy, and (ii) reducing sensor deployment effort. In a similar context, Park, et al. [27] integrated individuals' motion tracking sensors and BIM aiming to improve the personnel's positioning accuracy in dynamic and complex indoor construction sites. In a BIM-based indoor navigation study, Taneja, et al. [39] presented Industry Foundation Classes (IFC)-based BIM algorithms for automated generation of navigation models for map-matching of indoor positioning data. One of the studies that utilized high-tech visualization aids was Wang, et al. [29]. They addressed some principals for emergency management which led to a real-time fire evacuation guide. It was achieved by developing a BIM-based virtual environment supported by Virtual Reality (VR) incorporated with a game engine. A need for dynamically generating emergency scenarios was also noted in this study. In a similar context, Zhang and Issa [31] proposed a BIM-based Immersive Serious Gaming environment meant to capture a variety of human behaviors and decision making during emergency evacuation. In detail, BIM was employed in the game design phase to provide building environment information and emergency route network. Wang, et al. [30] used BIM to support fire safety management including evacuation assessment, escape route planning, and safety education. The evacuation assessment module was employed to calculate Available Safety Egress Time (ASET) in comparison to the Required Safety Egress Time (RSET) to examine evacuation capability. Using microscopic evacuation simulation enhanced with a detailed simulation environment was highly recommended in this study to replicate many of uncertainties during the process of evacuation. Recently, Cheng, et al. [33] conducted a BIM-ABM and FDS integration to investigate the evacuation capability of a complex offshore environment in the case of a fire emergency. They concluded that site layout has serious impact on evacuation planning, and utilizing BIM in the evacuation assessment is highly effective in complex environments such as congested construction sites.

The above literature review shows that assessment of evacuation process of complex environments (especially construction projects) has been done considering cause of an evacuation, and performance of consequent evacuation as distinct subjects of investigation. However, safety management of a complex environment is an issue which should be considered as a package of interdependent factors as discussed before. Thus, this research study is an effort to achieve this integration in evacuation risk assessment procedure considering potential for emergency occurrence, and capability for conducting a safe evacuation, simultaneously.

The contributions of this research study to existing literature can be summarized as follows:

1. Demonstrating the efficiency and reliability of the proposed approach towards evacuation risk assessment in which the potential for fire emergency occurrence, and potential for a proper evacuation response are proposed to be analyzed through an integrated approach.
2. Microscopically evaluating the evacuation of a site using a multi-objective approach that covers both aspects of quickness (Total Evacuation Time (TET)) and safety (congestion level).
3. Social Force Modeling of a complex construction site throughout the entire stages of the project schedule.
4. Investigating the effects of following behavior of emergency instructions on performance of evacuation of a complex construction site.

3. Methodology

The main purpose of this study is real-time determination of overall evacuation risk of a complex project during its construction phase. To achieve this purpose, we proposed a framework shown in Fig. 1 which consists of two modules that are working together based on provided project information. The first module determines the risk of occurrence of a fire emergency for every work zone. The second module evaluates the efficiency of evacuation from these work zones as a response to that emergency. The overall risk of evacuation is finally determined by the simultaneous analysis of these two modules. The main algorithm handles this collaboration between project information platform, emergency potential assessment module, and evacuation assessment module. An ignition Quantitative Risk Assessment (QRA) model is employed to investigate potential fire emergency for each work package. For the purpose of evacuation assessment, a model was developed based on collaboration of 4D-BIM and SFM to conduct microscopic simulations in a rich virtual environment. 4D-BIM provides accurate geometric and semantic information on the job site. SFM is used to simulate the individuals' attributes in the process of evacuation. The entire process is automatically conducted for every zone of the site and in every stage of the project schedule. However, the above procedures were executed under a parallel computing envelope to increase the practicability of the running time of the model which is tested on the case study of this paper (the case study is described in section 4.1 in details).

The remainder of the section of *Methodology* respectively addresses project information modeling, fire ignition risk assessment, and evacuation assessment.

3.1. 4D-building information modeling (4D-BIM)

The main objective of this paper is to analyze what triggers a need for evacuation, and how successful the evacuation is, through an integrated approach. To reach this target, this study takes advantage of the potential that BIM provides for safety management of a construction project. 4D-BIM actually adds an extra dimension of information to a project information model in the form of scheduling data. In this paper, a 4D-BIM platform (Fig. 2) is utilized to organize comprehensive project management information, also additional fire-related information about the potential of various work packages to trigger a fire emergency. Four types of data are obtained through this interface (Fig. 2):

i) Project management data: including project schedule, and allocated human/machinery/material resources
ii) 3D model of the project: containing real-world coordination of components
iii) Fire related data: including ignition potential of different construction tasks (calculation of ignition potential is explained in section 3.2 in details)
iv) Evacuation instruction: including location and specification of emergency pathways, emergency exits, and temporary safe gathering places/shelters

This platform is then used for generating the evacuation simulation environment due to the rich geometric and semantic information that it

Table 1
Summary of the reviewed studies in section "Related works".

Study	Case study				Simulation platform							Research approach					Information platform			
	High-Rise	Extend Site	Large-Scale Building	Tunnel and Station	SFM	CA[1]	ABM[2]	Serious Game	Commercial Fire Simulator (FDS and etc.)	Commercial Evacuation Simulator (EXODUS and etc.)	VR[3]	Optimization	Rout Advising	Risk Assessment	Evacuation Evaluation	Behaviour Investigation	BIM (Revit and etc.)	Project Schedule and Planning (MSP and etc.)	GIS	IFC Data
Frantzich [6]				●*					●											●
Rüppel and Schatz [23]			●					●	●		●				●	●				
Said, et al. [24]	●*						●						●			●				●
Wang, et al. [25]		●											●		●		●			
Li, et al. [26]			●						●			●					●			
Park, et al. [27]			●*										●				●			●
Shi and Liu [28]				●			●		●						●		●		●	●
Wang, et al. [29]			●					●			●		●				●			
Wang, et al. [30]			●						●				●		●		●			
Zhang and Issa [31]							●	●							●	●				
El Meouche, et al. [32]		●*				●			●			●	●	●					●	
Cheng, et al. [33]							●		●				●		●		●			
Marzouk and Al Daour [22]			●*				●						●		●		●	●		
Kim and Lee [34]		●*											●				●	●		
Galea, et al. [2]	●*									●					●	●				●

* Refers to construction project sites
Empty fields refer to the categories which are not among the headings.
[1] Cellular Automata.
[2] Agent-Based Modeling.
[3] Virtual Reality.

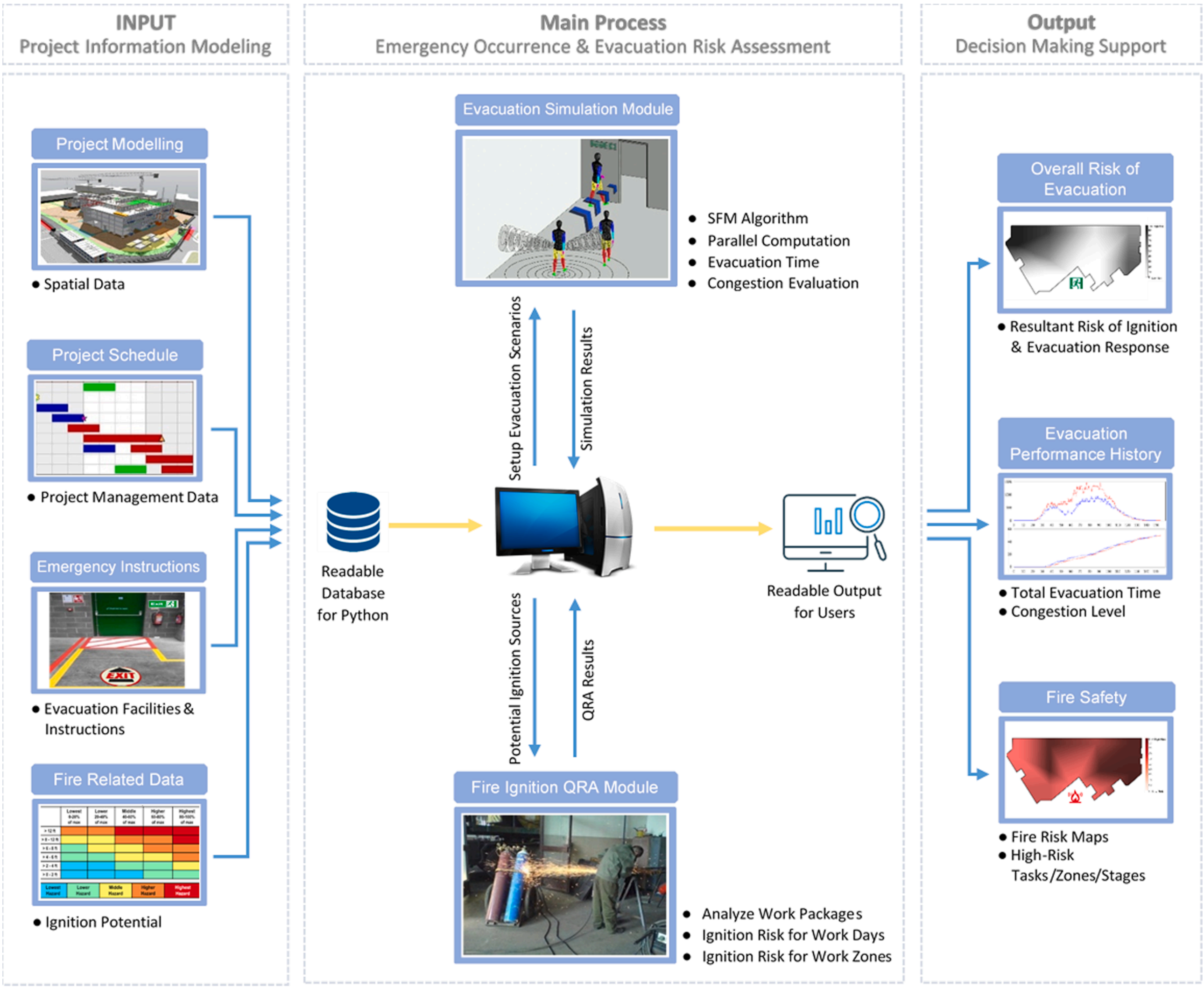

Fig. 1. The proposed process of overall evacuation risk assessment.

provides on a timely basis. Therefore, the ever-changing conditions of a construction site can be taken into consideration in the simulations, such as the effects that constructing a non-structural wall may have on the evacuation path network and also evacuation performance. Fig. 2 shows the interface which was designed to organize the project information in different categories. Using the open API of Autodesk Navisworks® and Autodesk Point Layout®, the authors developed this interface that collaboratively combines interfaces of two above-mentioned packages. Moreover, this interface can put out data in a readable format for the main evacuation simulation algorithm which is programmed in the Python programming language.

Data structure and information flow in the proposed framework are shown in Fig. 3. Autodesk Revit®[1], Autodesk Navisworks®, and Autodesk Point Layout® are used to interpret schedule data and geometric data in a readable input for SFM engine as shown in Fig. 3. API of Autodesk Revit and Autodesk Navisworks are also utilized to directly interact and facilitate data transformation. After obtaining all the building elements by Autodesk Revit, Autodesk Navisworks is used to adapt the project environment with the project management data. Meanwhile, Autodesk Point Layout is employed to convert the building environment to a coordination network matrix that is readable for the SFM engine. Similarly, emergency evacuation instructions (including emergency evacuation path network and exit gates) are determined by the Autodesk Point Layout in the form of a coordination matrix of destinations. The mentioned comprehensive information that 4D-BIM provides is finally used by the fire QRA module (to assess fire occurrence risk), and by the SFM module (to assess evacuation safety).

3.2. Fire occurrence risk assessment

After designing a project information interface in the previous section, this section deals with fire occurrence risk related to operating activities in each stage of the project schedule. 4D-BIM is used for providing the required information as stated before.

Proximity of flammable substances to ignition sources constitutes potential threats of fire and is responsible for the majority of reported fire emergencies in industrial facilities [40]. Gas/liquid leakage situations, portable fuel supply tanks, and existing combustible materials are some of the most important suppliers of these flammable substances. However, the equipment which are involved in various job tasks are considered as the main ignition sources (the project studied in this paper is described in section 4.1 in details). Investigating various activities and equipment in terms of involved flammable substances and their leakage potential is not in the scope of this study. Therefore, published tables which classify overall expected hazard of flammable substances and leakage potential, as well as level of safety control in various industrial

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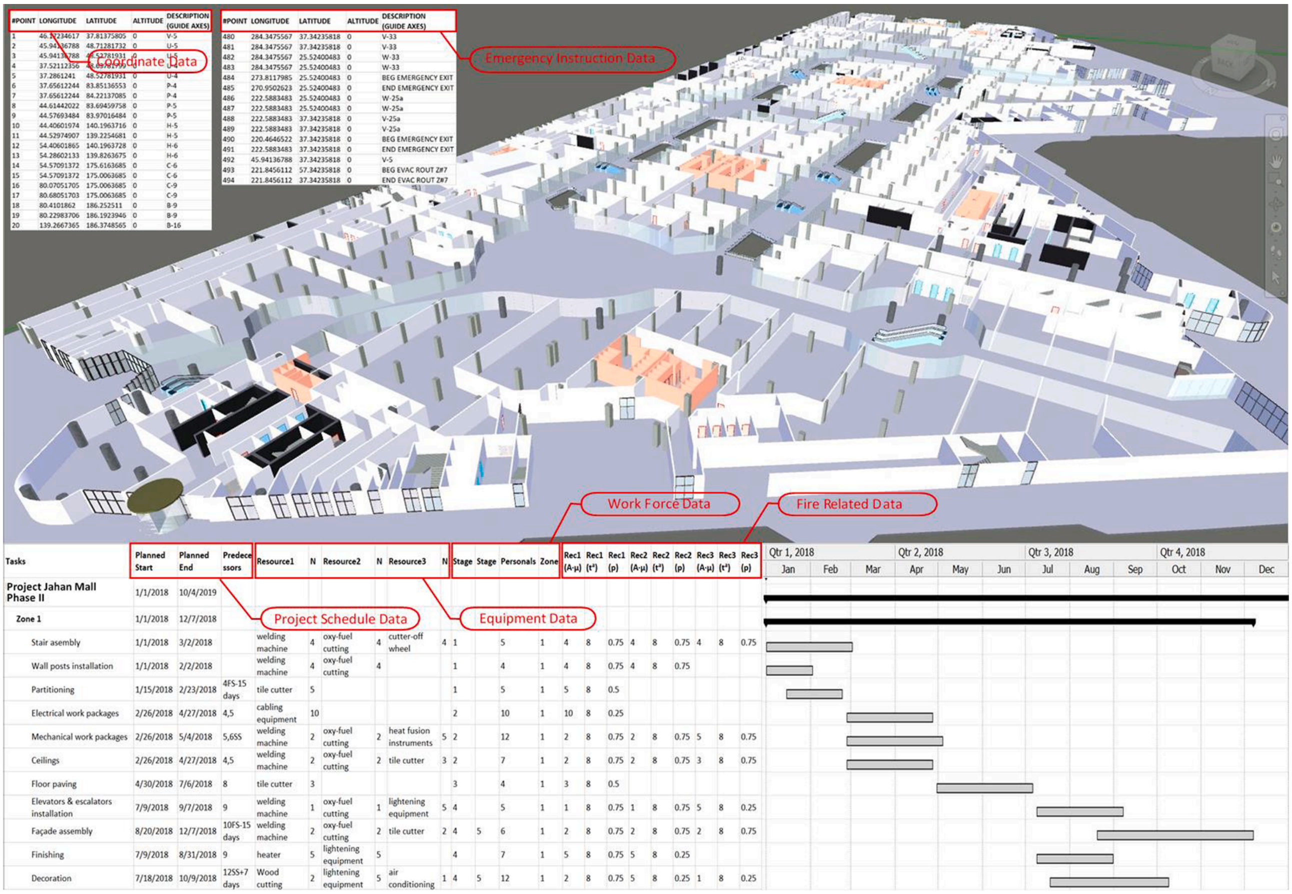
[1] This article is independent of Autodesk, Inc., and is not authorized by Autodesk, Inc.



#POINT	LONGITUDE	LATITUDE	ALTITUDE	DESCRIPTION (GUIDE AXES)
1	46.17234617	37.81375805	0	V-5
2	45.94136788	48.71281732	0	U-5
3	45.94136788	48.52781931	0	U-5
4	37.52112356	48.69781799	0	U-4
5	37.2861241	48.52781931	0	U-4
6	37.65612244	83.85136553	0	P-4
7	37.65612244	84.22137085	0	P-4
8	44.61442022	83.69459758	0	P-5
9	44.57693484	83.97016484	0	P-5
10	44.40601974	140.1963716	0	H-5
11	44.52974907	139.2254681	0	H-5
12	54.40601865	140.1963728	0	H-6
13	54.28602133	139.8263675	0	H-6
14	54.57091372	175.6163685	0	C-6
15	54.57091372	175.0063685	0	C-6
16	80.07051705	175.0063685	0	C-9
17	80.68051703	175.0063685	0	C-9
18	80.4101862	186.252511	0	B-9
19	80.22983706	186.1923946	0	B-9
20	139.2667365	186.3748565	0	B-16

#POINT	LONGITUDE	LATITUDE	ALTITUDE	DESCRIPTION (GUIDE AXES)
480	284.3475567	37.34235818	0	V-33
481	284.3475567	37.34235818	0	V-33
482	284.3475567	25.52400483	0	W-33
483	284.3475567	25.52400483	0	W-33
484	273.8117985	25.52400483	0	BEG EMERGENCY EXIT
485	270.9502623	25.52400483	0	END EMERGENCY EXIT
486	222.5883483	25.52400483	0	W-25a
487	222.5883483	25.52400483	0	W-25a
488	222.5883483	37.34235818	0	V-25a
489	222.5883483	37.34235818	0	V-25a
490	220.4646522	37.34235818	0	BEG EMERGENCY EXIT
491	222.5883483	37.34235818	0	END EMERGENCY EXIT
492	45.94136788	37.34235818	0	V-5
493	221.8456112	57.34235818	0	BEG EVAC ROUT Z#7
494	221.8456112	37.34235818	0	END EVAC ROUT Z#7

Tasks	Planned Start	Planned End	Predecessors	Resource1	N	Resource2	N	Resource3	N	Stage	Stage	Personals	Zone	Rec1 (A·μ)	Rec1 (t²)	Rec1 (p)	Rec2 (A·μ)	Rec2 (t²)	Rec2 (p)	Rec3 (A·μ)	Rec3 (t²)	Rec3 (p)
Project Jahan Mall Phase II	1/1/2018	10/4/2019																				
Zone 1	1/1/2018	12/7/2018																				
Stair asembly	1/1/2018	3/2/2018		welding machine	4	oxy-fuel cutting	4	cutter-off wheel	4	1		5	1	4	8	0.75	4	8	0.75	4	8	0.75
Wall posts installation	1/1/2018	2/2/2018		welding machine	4	oxy-fuel cutting	4			1		4	1	4	8	0.75	4	8	0.75			
Partitioning	1/15/2018	2/23/2018	4FS-15 days	tile cutter	5					1		5	1	5	8	0.5						
Electrical work packages	2/26/2018	4/27/2018	4,5	cabling equipment	10					2		10	1	10	8	0.25						
Mechanical work packages	2/26/2018	5/4/2018	5,6SS	welding machine	2	oxy-fuel cutting	2	heat fusion instruments	5	2		12	1	2	8	0.75	2	8	0.75	5	8	0.75
Ceilings	2/26/2018	4/27/2018	4,5	welding machine	2	oxy-fuel cutting	2	tile cutter	3	2		7	1	2	8	0.75	2	8	0.75	3	8	0.75
Floor paving	4/30/2018	7/6/2018	8	tile cutter	3					3		4	1	3	8	0.5						
Elevators & escalators installation	7/9/2018	9/7/2018	9	welding machine	1	oxy-fuel cutting	1	lightening equipment	5	4		5	1	1	8	0.75	1	8	0.75	5	8	0.25
Façade assembly	8/20/2018	12/7/2018	10FS-15 days	welding machine	2	oxy-fuel cutting	2	tile cutter	2	4	5	6	1	2	8	0.75	2	8	0.75	2	8	0.75
Finishing	7/9/2018	8/31/2018	9	heater	5	lightening equipment	5			4		7	1	5	8	0.75	5	8	0.25			
Decoration	7/18/2018	10/9/2018	12SS+7 days	Wood cutting	2	lightening equipment	5	air conditioning	1	4	5	12	1	2	8	0.75	5	8	0.25	1	8	0.25

Fig. 2. 4D-BIM interface used in the proposed model for data acquiring.

facilities were used in this study. Then, ignition probability for the situation where a flammable substance is exposed to a few ignition sources is calculated through a macro-level approach. A similar approach is adapted by many of the related studies such as Moosemiller [41], Taylor [42] and Pula, et al. [43]. However, in this study it is assumed that occurrence of an ignition wherever inside one zone will release the order of evacuation for entire of that zone. The following were tracked in order to recognize clustering of the studied facility in this paper in terms of expected hazard of flammable substances and ignition potential.

- **Involved equipment clustering:** This study investigates the post-structural phase of a construction project which is described in section 4.1 in detail. In this phase of the studied project, the equipment involved are limited to machines and tools with moderate physical size, voltage, and performance. Hence, the equipment level is selected as 'medium' according to Table 2 (which is a part of the full-size table presented by Spencer, et al. [44]).
- **Site condition:** According to Table 3 by Rew and Daycock [45] who developed the model presented by Spencer, et al. [44], the predefined construction site including medium level equipment (from Table 2) is assumed to be 'process area including medium equipment', and it is clustered as 'non-hazardous' area. Moreover, the studied project under the investigation is clustered as 'internal' site since it is studied during the post-structural phase. Auxiliary facilities related to a typical construction site (such as storages, labor resorts, and in-site offices) are not subject to analysis in the present study.
- **Safety control:** Ignition control is determined to be 'typical' according to the division provided in Table 4 by Rew and Daycock [45], and considering the safety control's condition for the studied project. However, within the above-mentioned descriptions, the overall ignition potential is in 'limited level'. In this Table, 'typical' rank is assigned conditions under which the site is designed to meet the related standards and is maintained regularly. Specifically, 'typical' refers to sites where ignition is eliminated in normal operations, but there is potential for change in circumstances which might result in an occasional ignition.
- **Ignition risk:** The ignition risk and other related parameters for a situation where a flammable substance is exposed to a few ignition sources is determined using Eq. (1) by Rew and Daycock [45] (which is described in the following in detail) and the tables provided by developers of the model.

To calculate the above-mentioned ignition risk we picked the model that was initially developed by Spencer and Rew [46], and improved by Rew and Daycock [45]. The main advantages of the mentioned model are: (i) ability to incorporate various fire-related data, (ii) applicability to many types of environments (such as warehouses and construction sites), and (iii) considering a wide variety of ignition sources within hazardous as well as non-hazardous areas [43]. So far the model has been used and acknowledged in a wide range of studies such as Moosemiller [41], Taylor [42] and Pula, et al. [43]. This model can be efficient in modeling fire hazard conditions encountered on construction sites due to its ability in covering various types of ignition sources and different possible scenario types [43,47]. This model coupled with some adjustments to cover the condition of this research. However, the parameters of the model are picked from tables presented by Rew and Daycock [45] considering the expected hazard of flammable substances and the ignition control level which were determined above. It is also assumed by this model that the flammability and amount (concentration for the gas) of the flammable substance is in the range that is needed to be immediately ignited when it is exposed to an ignition source. The following equation represents probability of no ignition in the situation

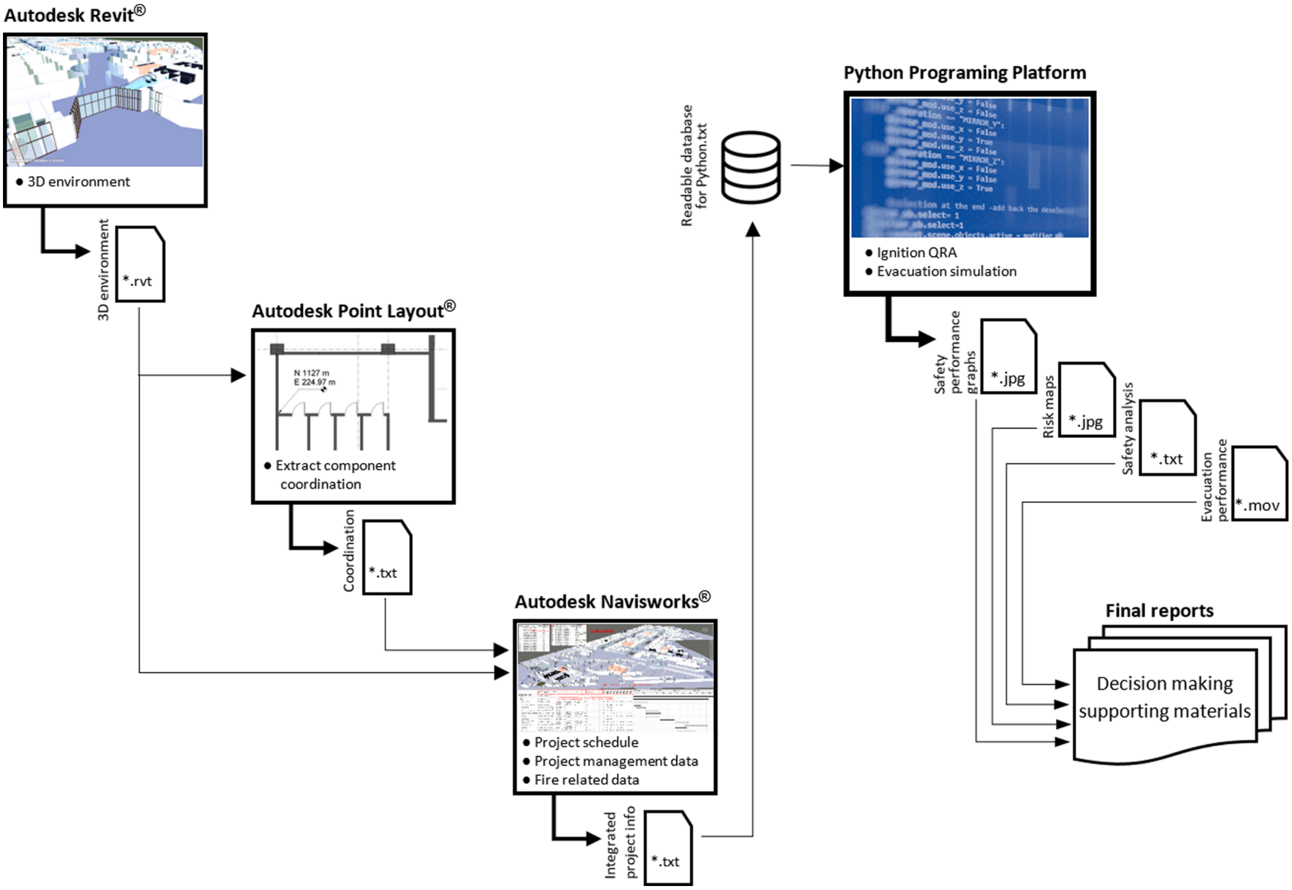


Fig. 3. Data structure and information flow in the proposed framework.

Table 2
Equipment level for generally involved machinery.

Involved Machinery	Equipment Level
Large motors, pumps, etc.	Heavy
Smaller motors, pumps, etc.	Medium
Low voltage switches and contacts only	Light

where a pre-described flammable substance is exposed to a few ignition sources [45]:

$$P_{no-ig} = \sum_{i=1}^{m}\sum_{j=1}^{n} exp(-A_i\mu_j[1-(1-a_jp_j)e^{-\lambda_j p_j d_j}]) \tag{1}$$

$$a_j = \frac{t_j^a}{(t_j^a + t_j)} \tag{2}$$

$$\lambda_j = \frac{1}{(t_j^a + t_j)} \tag{3}$$

In the above equations, A_i is the total area i of the site with the potential for ignition due to a flammable substance. In the present study, it is assumed that the probable flammable substance is uniformly spread in the investigated area i. μ_j is the density of ignition source j within the area i and refers to the number of a given type of ignition source per unit area. a_j is the rate of activation of source j and is in the form of Eq. (2) where in this equation t_j and t_j^a respectively represent the average period between activation of source j and the average period of activation of that source.

Since in this study there is a single 8-hour work shift in each 24 h, these parameters are set to be 24 h and 8 h respectively (the project studied in this paper is described in section 4.1 in details). Here λ_j represents the proportion of time that source j is active and is in the form of Eq. (3). Moreover, d_j is the duration of activation of source j. Here it is assigned the same value as that of t_j^a. Finally, p_j is the ignition potential for source j in area i. Spencer, et al. [44] and some other researchers have tabulated values of the ignition potentials of different equipment in

Table 3
Generic on-site land-use types.

Land-use type	Classification	Location
Car parks	Non-hazardous	External
Roads	Non-hazardous	External
Controlled roads	Classified	External
Waste ground	Non-hazardous	External
Boiler house	Non-hazardous	Internal
Flames: continuous	Non-hazardous	Internal External
Flames: infrequent	Non-hazardous	Internal External
Flames: intermittent	Non-hazardous	Internal External
Kitchen facilities	Non-hazardous	Internal
Process area – ‘heavy’ equipment	Non-hazardous	Internal External
Process area – ‘medium’ equipment	Non-hazardous	Internal External
Process area – ‘light’ equipment	Non-hazardous	Internal External
Classified area	Classified	Internal External
Storage	Non-hazardous Classified	External Internal
Office	Non-hazardous	Internal

Table 4
Ranking system for quality, or effectiveness of ignition source controls.

Type	**Permanent Ignition Controls**	**Temporary Ignition Controls**
	Design features such as intrinsically safe electrical equipment or earthing of system	Controls with human factors, such as permit systems and access control
Ideal	Design and maintenance ensures no ignition source at any time	Permits and procedures ensure no ignition sources introduced at any time
Excellent	Equipment well designed and maintained to eliminate risk – ignition only arising from rare events (e.g. unforeseen failure of equipment)	Permit well designed and implemented – ignition source only arising from unforeseen failure of several systems (e.g. human error AND failure of back-up systems)
Typical	Equipment designed to meet standards and maintained regularly – ignition eliminated in normal operation but some potential for equipment failure or changing circumstances to result in an occasional ignition source	Permit well designed and implemented – ignition eliminated in normal circumstances but some potential for human error to result in an occasional ignition source
Poor	The design does not meet precise standards and poorly maintained – resulting in significant potential for ignition sources to occur	Permits and procedures employed but significant potential for failures – primarily due to poor training, supervision and permit management systems
None	No adherence to standards and little maintenance – the significant potential for ignition sources to occur	No use of permit system – maintenance and special operations (e.g. fueling) occur with little or no control – significant potential for ignition sources to be introduced

different industrial areas regarding site conditions with respect to expected hazards of flammable substances and ignition control level. However, Taylor [42] collected and organized the majority of data acquired by those researchers. Thus, the parameter values for the existing ignition sources in this research study are picked according to the mentioned tables considering the predetermined expected hazard of flammable substances and ignition control level of the studied project which were described above. Since a limited number of ignition sources which exist in the studied project are not exactly documented in Spencer, et al. [44], we used predefined general clustering as it was used in their study to estimate these parameters. These tables are not presented here due to their huge size. Numerical values of parameters of the model are presented in Table 5.

Finally, Eq. (4) presents fire ignition risk in zone *i*. In this equation, term $Risk_{ignition}$ returns to the potential that a fire emergency will occur in the given construction site. This equation is coupled with parameters which are picked from the aforementioned Tables.

$$Risk^{i}_{ignition} = \left(\sum_{j=1}^{n} exp\left(-A_i\mu_j\left(1-\left(1-a_jp_j\right)e^{-\lambda_jp_jd_j}\right)\right)\right) \times 100 \tag{4}$$

The developed algorithm calculates fire occurrence risk (using Eq. (4)) for various activities operating in every stage of the project schedule considering the involved equipment. After the fire occurrence risk of a particular work zone is determined, the evacuation of that zone, as a response to that fire emergency, is investigated as explained in the following section.

3.3. Evacuation assessment

The method to determine the risk of occurrence of a fire emergency was described in the previous section. This section addresses assessment of evacuating the site, in response to the emergency situation. To do so, the remainder of this section is devoted to simulation of evacuation and evacuation performance evaluation, respectively.

Table 5
The definitions and numerical values of the parameters.

Parameter	Value*	Definition
Fire QRA parameters		
t_j	24 h	Average period between activation of source *j*
t_j^a	8 h	Average period of activation of source *j*
d_j	8 h	Duration of activation of source *j*
SFM parameters		
v_i^0	[1.1–1.3] m/s	Uniform distribution of individual's preferred speed in the emergency situation
τ_i	0.5 sec	The pedestrian's reaction time (the time step for updating pedestrians' position)
A_i	2000 N	Constant parameter
B_i	0.08 m	Constant parameter
k	1.2×10^5 kg/s^2	Constant parameter
κ	2.4×10^5 kg/m.s	Constant parameter
Crowd danger parameters		
Cl_{max}	15.0 m^{-1}	Maximum congestion level for unidirectional movement type
κ	0.0929 m^2	Direction type's coefficient for unidirectional movement type
Pedestrian specification		
m_i	[75–85] kg	Uniform distribution of pedestrians' mass
r_i	0.25 *m*	Pedestrians' radius

* Some of the parameters' values are based on the assumptions and limitations of this study.

3.3.1. Evacuation simulation

In this study, SFM is utilized to simulate the evacuation scenarios. SFM is a multi-particle self-driven model introduced by Helbing and Molnar [16] which has been validated with data obtained from empirical and natural events [21,48–50]. This model is validated in duplicating complex pedestrian flow scenarios such as bottleneck flow [51], waiting and queueing behavior [52], and high-density moving crowd [21] which could be expectable in complex construction sites. In addition, force-based models generally are capable of duplicating crowd maneuvering in complex environments where the surrounding environment of a moving crowd may change rapidly from time to time [53]. These advantages could make SFM an appropriate model to be used for simulating the evacuation of complex construction sites. To accomplish the evacuation sector of this study, the developed version of SFM in the Python platform by Wang [54] was employed. Individuals in SFM are affected by an inner mental force and also surrounding interaction forces [16]. The basics of SFM are presented in the following paragraphs. The model is also calibrated based on the assumptions of Helbing, et al. [55] and Johansson, et al. [50]. However, values of constant parameters are chosen based on the particular condition of evacuation scenarios of the present study as follows:

- Population density condition in the event of emergency evacuation is normal.
- Sight from the surrounding environment for all the evacuees is clear, and there is no smoke effect.
- All the evacuees are grown-up and no child and elderly are among the escaping crowd.
- There is no unusual issue in the evacuation path network of the facility such as slippery walking surfaces.
- Pedestrians move individually and not in a group.
- Type of movement of the crowd is unidirectional (pedestrians only leave the facility).
- The geometry of an evacuee's body is estimated to be a circle with a certain radius.
- Individuals' behavior is affected by the emergency situation during the whole process of evacuation.

The main equation of SFM is in the form of Eq. (5).

$$m_i \frac{d\overrightarrow{v}_i}{dt} = m_i \frac{v_i^0(t).\overrightarrow{e}_i^0 - \overrightarrow{v}_i(t)}{\tau_i} + \sum_{j(\neq i)} \overrightarrow{f}_{ij} + \sum_{o} \overrightarrow{f}_{io} \tag{5}$$

where $m_i(v_i^0(t) \bullet \overrightarrow{\mathrm{e}}_{\mathrm{i}}^0 - \overrightarrow{\mathrm{v}}_{\mathrm{i}}(\mathrm{t}))/\tau_{\mathrm{i}}$ refers to the inner driven force. So pedestrian i with mass m_i drives through a certain direction $\overrightarrow{e}_i^0$, while his/her actual velocity $\overrightarrow{v}_i$ tends to reach the desired speed v_i^0 in each reaction time τ_i (which is set to be 0.5 s in this study). A pedestrian's mass is picked from the range of [75-85] *kg* where the body radius of an individual is estimated to be 0.25 *m*. $\overrightarrow{f}_{ij}$ describes the interaction force drilled from other pedestrian *j*, and is in the form of Eq. (6). In addition, $\overrightarrow{f}_{iw}$ represents the repulsive force from the wall *w* (Eq. (7)). Thus, the acceleration of pedestrians in this model is the result of the concurrent effect of these forces (Eq. (5)).

$$f_{ij} = (A_i.e^{\frac{(r_{ij}-d_{ij})}{B_i}} + k.g(r_{ij} - d_{ij}))\overrightarrow{n}_{ij} + \kappa.g(r_{ij} - d_{ij})\Delta v_{ij}^t.\overrightarrow{t}_{ij} \tag{6}$$

where $A_i\hat{\mathrm{A}}\cdot e^{(r_{ij}-d_{ij})/B_i}$ denotes the repulsive force between pedestrians *i* and *j*. A_i and B_i are equal to 2000 N and 0.08 m as the constant parameters of the model, respectively. $\overrightarrow{n}_{ij}$ is the normalized vector pointing from pedestrian *i* to *j*. $k\hat{\mathrm{A}}\cdot g(r_{ij} - d_{ij})$ and $\kappa\hat{\mathrm{A}}\cdot g(r_{ij} - d_{ij})\Delta v_{ij}^t\hat{\mathrm{A}}\cdot\overrightarrow{t}_{ij}$, respectively calculate the counteracting body compression force and sliding friction force between individuals *i* and *j* in the moment of contact. *k* and κ are equal to 1.2×10^5 kg s^{-2} and 2.4×10^5 kg m^{-1} s^{-1} , respectively based on model calibration [50]. The function *g(x)* is zero if pedestrians do not touch each other. Otherwise, it is equal to the argument *x* which returns the difference of r_{ij} (sum of body radiuses of individuals *i* and *j*) and d_{ij} (distance between individuals *i* and *j*). Δv_{ij}^t and $\overrightarrow{t}_{ij}$ represent tangential velocity difference and tangential direction, respectively. The third phrase in Eq. (5) represents the interaction force between individual *i* and surrounding wall *w* (Eq. (7)).

$$f_{iw} = (A_i.e^{\frac{(r_i-d_{iw})}{B_i}} + k.g(r_i - d_{iw}))\overrightarrow{n}_{iw} - \kappa.g(r_i - d_{iw})(\overrightarrow{v}_i.\overrightarrow{t}_{iw})\overrightarrow{t}_{iw} \tag{7}$$

In Eq. (7) the definitions of the arguments are the same as those in Eq. (6), but they represent the interaction between pedestrian *i* and wall *w*. Numerical values of parameters of the model are presented in Table 5.

Using microscopic models requires huge computation efforts and this challenge elevates when a high number of scenarios must be simulated for the numerous stages of the project schedule [10,11]. This justifies why utilizing microscopic models for time-varying condition of construction sites is not sufficiently addressed (as it was stated in section 2). However, it has been tried to overcome this challenge by coupling a parallel computing method with the SFM simulation engine. In this method, real-time calculations of pedestrians' interaction forces were manually assigned to the octet computer processors, utilizing a multiprocessing library [56] while the automated launcher module efficiently arranged portfolio of the scenarios to be simulated. Hence, a considerable number of evacuation simulations for every part of the site, and in every stage of the project schedule can be run in a practical time.

In the following, the criteria used for evaluating the simulated evacuation scenarios are discussed in detail.

3.3.2. Criteria for success of evacuation

In this study, two performance metrics are employed for evaluating success of an evacuation process; (i) Total Evacuation Time (TET), which evaluates quickness of the process, and (ii) congestion level, which evaluates safety of the process.

3.3.2.1. Total evacuation time (TET). TET represents speed of vacating the facility which refers to the duration of time to evacuate all the occupants to a safe place [57]. In this paper, each part of the construction site is subject to investigation of how fast it could be evacuated considering the real-time conditions of the site. TET is then determined by a stopwatch after the last evacuee reaches the predefined safe place. Accordingly, the risk associated with evacuation performance in terms of required evacuation time is determined by Eq. (8) where ET_i is the evacuation time of individual *i*, and ET_{max} represents the overall value of 450 s as cautionary evacuation time for industrial facility types, regardless of the site specifications [58] (the project studied in this paper is described in section 4.1 in details). The term $Risk_{evacuation}^{ET}$ actually determines how an evacuation scenario might be unsafe in terms of evacuation duration time. T^{pre} also is the pre-movement time that takes for individuals to decide to start the evacuation process and is assumed to be 97 s as the mean value of distribution of pre-response time in various evacuation scenarios in the industrial occupancy according to the tabulation by *SFPE handbook of fire protection engineering* [59]. In the context of this research, pre-response time is not the subject to investigation and it is assumed that all the personnel working in the job site respond to the order of evacuation within the mentioned pre-movement time. In the probable cases where TET is higher than ET_{max}, the value of $Risk_{evacuation}^{ET}$ is equal to 1, and the corresponding scenario is reported as a failed scenario that requires immediate revision by project managers.

$$\mathrm{Risk}_{\mathrm{evacuation}}^{\mathrm{ET}} = (\max(\mathrm{ET}_i)/(ET_{max} - T^{pre})) \times 100 \tag{8}$$

3.3.2.2. Congestion level. A poorly organized crowd is the first responsible cause of casualties in an evacuation process [60,61]. Several studies such as Polus, et al. [62] exist which have addressed pedestrian casualties in overcrowded situations and have presented metrics to measure safety of a moving crowd. Evacuation casualties were believed to be the only consequence of congested flow of pedestrians until Helbing, et al. [60] introduced the concept of evacuation efficiency drop as another undesirable consequence of overcrowded conditions. Although some earlier studies exist which investigated evacuation efficiency such as Løvås [63] who considered speed-density relationship to analyze egress efficiency, a tangible decline in egress efficiency in high-density conditions was observed by Helbing, et al. [60]. This issue is raised in bottlenecks and narrow pathways and highlights the importance of congestion level in complex environments such as construction project sites.

A well-documented model for evaluating congestion level was introduced by Feliciani and Nishinari [8] which was based on the principals of the study by Helbing, et al. [49]. This model was tested on a wide range of crowd flow patterns to be calibrated [64]. This model was also experimentally validated within various scenarios [8,65]. The model introduced by Feliciani and Nishinari [8] considers the real-time local density associated with moving crowd. Accordingly, this model can be efficiently adopted for the case of this study to measure the congestion level of evacuation of the studied complex construction site. The model by Feliciani and Nishinari [8] was then employed here to quantify congestion level. *Crowd danger* (*Cd*) function is defined in Eq. (9) in terms of population density (ρ) and crowd movement type as follows:

$$Cd(\rho) = \rho.Cl_{\max}(1 - e^{-\kappa\rho}) \tag{9}$$

Cl_{max} is the overall maximum value of congestion level (regardless of density) which is based on crowd movement pattern. The numerical value of this parameter as well as other parameters of the model is presented in Table 5. According to the condition of this study, the movement type of the evacuees is determined as unidirectional movement type [8] where all individuals try to depart the site and there is no entry to the site. κ is an empirical parameter which describes type of pedestrian movement and is selected to be 0.0929 m^2 considering unidirectional movement [8]. To determine the parameter ρ, the subjected facility with area of $C\ m^2$ is divided into 1×1 m cells. Then, a module is developed to count the number of pedestrians in each cell, in each time step of the evacuation process. Finally, the risk associated with evacuation performance in terms of congestion severity is calculated by Eq.

(10). $Risk_{evacuation}^{cong}$ determines how an evacuation scenario might be unsafe in terms of congestion severity for the moving crowd. In this equation ρ_c^t is population density of cell *c* in time step *t*. Cd_{max} (in the form of Eq. (11)) represents the maximum value of *Crowd danger* considering conservative population density (ρ_{max}) of 3.8 $persons/m^2$ for a moving crowd in the emergency situation. This population density corresponds to no movement conditions (according to the *SFPE handbook of fire protection engineering* [59]).

$$\mathrm{Risk}_{\mathrm{evacuation}}^{\mathrm{cong}} = \left(\sum_{t=1}^{TET}\sum_{c=1}^{C}\mathrm{Cd}(\rho_c^t)\right)/(\mathrm{Cd}_{\max}.C.TET) \times 100 \tag{10}$$

$$Cd_{max} = \rho_{max}.Cl_{max}\left(1 - e^{-\kappa\rho_{max}}\right) \tag{11}$$

4. The proposed model

The main objectives of this study are i) dynamical assessment of risk of occurrence of an emergency at a large-scale construction site, and ii) investigation of safety and speed with which the site could be evacuated in response to that emergency. To reach this target, an algorithm (Fig. 4) was developed in order to provide a basis for real-time collaboration of 4D-BIM, fire occurrence QRA, and SFM simulator. Thus, using the facility's information that 4D-BIM provides, fire QRA module determines the risk of occurrence of a fire emergency, and evacuation assessment module evaluates the evacuation process as the response to that fire emergency. This process is conducted for every part of the site, in every project stage according to the project schedule. The algorithm presented in Fig. 4 initially receives the facility's information and project management data, containing the following items, which are supplied by the developed 4D-BIM interface:

- Precise coordination of the facility's structural and non-structural components.
- A planned schedule for constructing each component.
- Estimated location of temporary components, equipment, and human resources which are allocated to work packages.
- Fire specifications related to equipment and materials which are involved in each work package.
- Emergency means of egress such as predefined escape pathways and emergency exits.

Utilizing a validated simulation engine as well as real input data for simulation environment could guarantee the reliability of the final results.

In the next step, the fire QRA module is called to assess the risk of occurrence of a fire emergency in each part of the site regarding the scheduled activities in that part (fire risk sector marked in Fig. 4). At the same time, the possible scenarios representing evacuation of different work zones are defined for SFM simulator functions (evacuation sector marked in Fig. 4) considering real-time conditions of the site. These functions are then distributed among octet processors for parallel execution (in the multi-processing sector marked in Fig. 4). Practicability of the model in terms of computation time was at risk due to the huge amount of SFM calculations required for simulating the evacuations of all the stages of the project schedule. To tackle this computation challenge, parallel computing technique was coupled with the developed model to be tested in the studied case of this paper (which is described in section 4.1 in details). Meanwhile, the possible event of emergency evacuation is evaluated by the required time (TET) and safety aspect (congestion level). Finally, a comprehensive analysis is available as the output of the framework including (i) fire occurrence risk maps, (ii) evacuation performance contours, (iii) overall risk maps which represent the resultant risk of fire emergency occurrence and evacuation in response, and (iv) history of the mentioned risk types during project schedule. The framework also highlights particular site zones, activities, and project stages in which their overall risks exceed the predefined safe limits, which itself provides an opportunity for safety management team to revise the safety management strategy of those risky stages. In this regard, L^{IR} and L^{ER}, respectively refer to the lower limit of high-risk range for ignition risk and evacuation safety risk (Table 6) and are set equal to the bound of 75 in the present study. The risk ranges are defined by the safety management team and are set according to Table 6 in this study. The described framework was developed in Python programming utilizing a machine equipped with octet processors (Intel Core i7/7700 HQ/2.80 GHz) and 16 GB RAM with a Linux operation system.

4.1. The case study

The introduced platform was implemented in Jahan Mall mega project, located in Mashhad, Iran, which consists of a commercial area, shopping center, entertainment facilities, extensive landscape, and a multi-functional hotel, with a total area of 70,000 m^2. In specific, the grand floor of the central sector which extends over 55,000 m^2 is selected for pilot study and hereafter it will be called the project. Due to privacy concerns, the complete scheme of the project management information is not shown here. The construction site of the project was divided into 9 distinct zones (Fig. 5), including different work packages that are scheduled to be executed in 9 stages. In this context, the project is broken down into 12 principal work packages, where each work package itself is broken down into up to 3 sub-tasks. The equipment required for each sub-task is allocated. Then, fire potential data are assigned to each one. Human resources are also allocated to the subtasks where they are laterally subject to evacuate in the simulated events of emergency. Using the developed 4D-BIM interface, the coordination of emergency evacuation pathways and exit gates are acquired by the user, and by the click of mouse.

4.2. Assumptions and limitations

This research study is conducted under the following assumptions and limitations and relaxing any of these limitations can be a potential subject for future studies:

- The equipment involved in different work packages (such as welding machines, lightening equipment, cutter-off wheels, and heaters) are solely responsible for fire ignition.
- Personnel are familiar with the site environment. Thus, there is no need for evacuation leadership in evacuation scenarios.
- Congestion effects of merging crowd from the upper floors are not considered in evacuation scenarios.
- Usual crew movement within a site is ignored and the crew of a work package is considered to be still at its operation location all day.
- Evacuation process will certainly take place in response to an occurred fire emergency.
- Fire smoke propagation is not considered and it does not affect the evacuees' maneuvering.

5. Results and discussion

The proposed model was employed in the described construction project and the obtained results are reported in this section. An evacuation simulation snapshot is also presented in Fig. 6 in order to give a better insight into the simulated evacuation environment.

5.1. Multi-objective evaluation of evacuation scenarios

Evaluating performance of emergency evacuation is a multi-objective problem where both timing and crowd safety issues are the main concerns to be taken into consideration as mentioned before. To demonstrate this circumstance, we analyzed performance of evacuation scenario of stage 2 with respect to either evacuation time (Fig. 7(a)) or

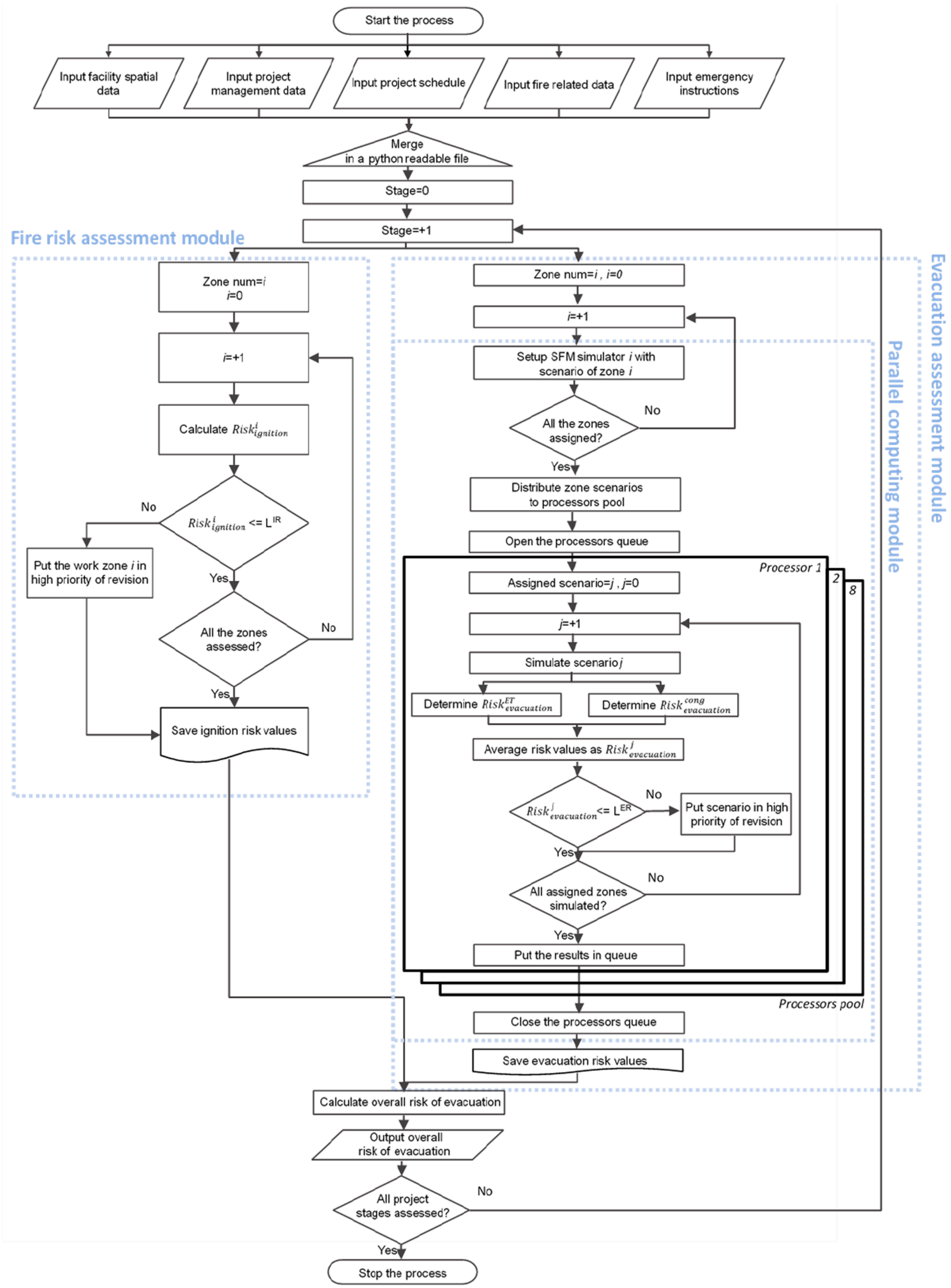


Fig. 4. Flowchart of the proposed evacuation risk assessment framework.

Table 6
Risk clustering and severity ranking.

Risk Type	Low-Risk	Moderate-Risk	High-Risk
Fire occurrence	0–25	25–75	75–100
Evacuation performance (TET* consideration)	0–25	25–75	75–100
Evacuation performance (congestion level consideration)	0–25	25–75	75–100
Evacuation performance (multi-objective consideration)	0–25	25–75	75–100
Overall risk of evacuation	0–25	25–75	75–100

* Total Evacuation Time.

congestion level (Fig. 7(b)). The numerical results are presented in Table 7. It is obvious that if evacuation is evaluated in terms of evacuation time alone, zone 9 (in Fig. 7(a)) is recognized to be a high-risk zone. However, if congestion level is the only criterion for success, zone 9 is not a challenging work zone to evacuate since it is a low-risk one. Finally, the average of the above-mentioned metrics, as multi-objective evaluation (Fig. 7(c)), revealed that evacuation process of zone 9 is accompanied with moderate levels of risks. Therefore, multi-objective evacuation evaluation could provide more reliable results representing the risks associated with evacuation performance (including TET and congestion level). Similar results could be achieved by comparing zone 2 and zone 9.

In the process of multi-objective evacuation evaluation, in addition to averaging the congestion level and TET, a time threshold was set to warn the project managers about scenarios with high TET (as it was explained in section 3.3.2.1). However, finding the most effective method for multi-objective evaluation of evacuation of a construction site could be itself a research potential for the future works.

5.2. *Overall risk of evacuation*

So far, we have demonstrated that project safety in terms of performance of a possible evacuation could be assessed in a more reliable way when the safety of the escaping crowd is taken into consideration in addition to Total Evacuation Time. In the following, the overall risk of evacuation is investigated. Overall risk of evacuation is actually the resultant risk of occurrence of a fire emergency and risks which are associated with conducting evacuation in response to that emergency. The performance of consequent evacuation, however, is evaluated multi-objectively. The developed model was tested on the post-structural phase of the project. However, as it was assumed previously, the equipment which are involved in various job tasks are considered as the main ignition sources in this study (section 4.1). Fig. 8 (a-c), respectively show fire occurrence risk map, evacuation performance risk map, and the overall evacuation risk map for stage 2 of the project, as an instant for representation. The numerical results are also presented in Table 8 where the values for the overall evacuation risk are actually averages of the two mentioned risks. As it is obvious in Fig. 8(a-c), there is a moderate risk for ability to successfully evacuate zone 9 while a high risk of fire ignition is seen in that zone. This emphasizes the fact that none of the mentioned risks can realistically describe evacuation risk when considered individually. This dichotomy confirms the issue that was stated earlier at the beginning of this paper, i.e. evacuation risk for a construction project may not be realistically assessed when the risks associated with evacuation performance are considered alone. So, the simultaneous consideration of (i) what triggers a need to conduct an evacuation (fire emergency occurrence potential), and (ii) the performance of evacuation as a response to that emergency (associated risks with evacuation performance) can result in more reliable evacuation risk assessment. Fig. 8(c), however, could provide a more realistic insight into the overall risk of evacuation of the project.

Fig. 9(a-c) present a perspective from the history of investigated risks during the project execution. Comparing Fig. 9(a) and Fig. 9(b) demonstrates the difference between risk assessed in the initial stages, where fire risks are considerably higher than evacuation risks. Investigating the project management data revealed the reason behind this variation. In the initial stages of the project, some job tasks are scheduled to be operated which engage high-risk equipment (such as welding machines) which have high potential to ignite a fire during these stages. However, there are a few components constructed in these stages and evacuees can

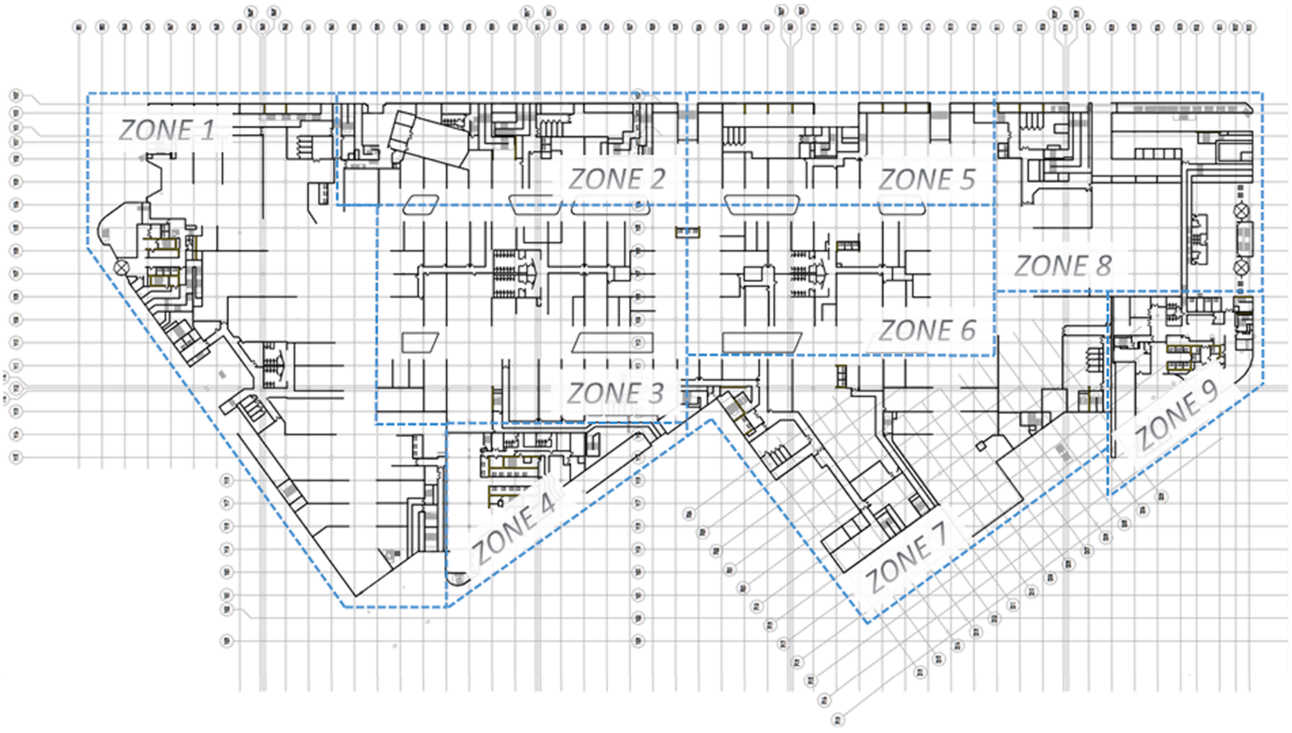


Fig. 5. The project's building environment and partitioning.

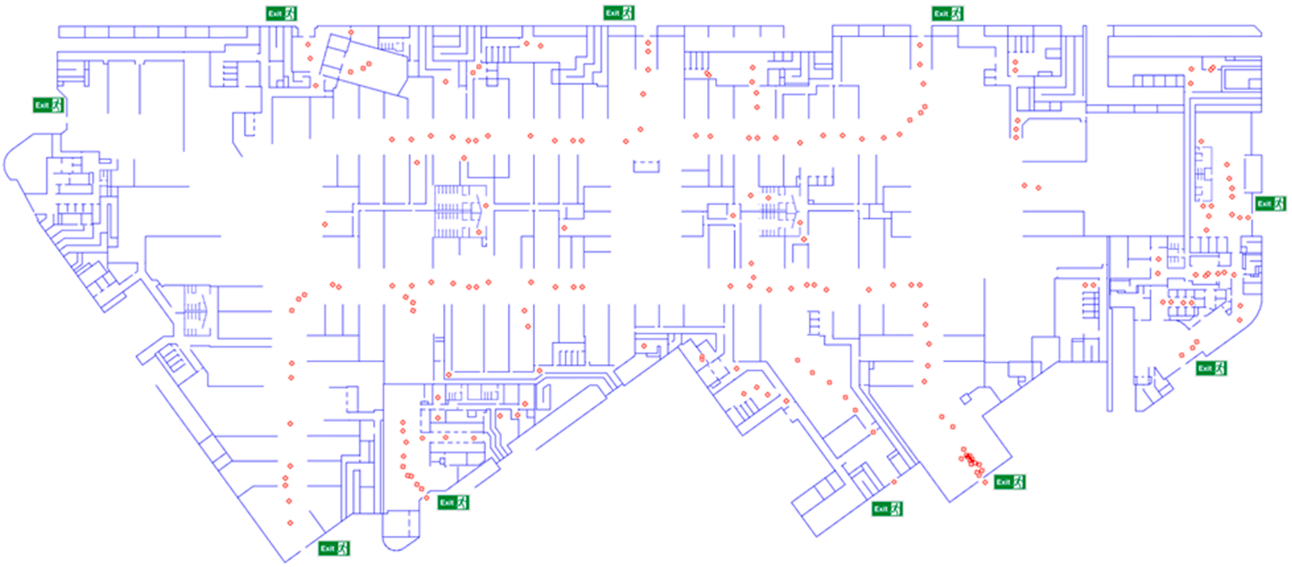


Fig. 6. A snapshot of the evacuation simulation of stage number 6 (i.e. the most crowded stage of the project schedule). Note: Red circles represent the evacuees and are exaggerated in terms of dimension for better illustration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

move inside the site easily. Thus, there are low levels of safety risk for conducting evacuation process. In other words, despite the high potential for fire accident in the initial stages, conducting evacuation process is expected to be easy and safe in these stages. This reveals the efficiency of the proposed model in describing the realistic risk of evacuation as the overall risk of fire occurrence and the pursuing evacuation in response to fire (Fig. 9(c)). As many of work packages are scheduled to be executed in parallel during stage 4, high number of personnel and equipment are expected to be operating in the job site during this stage. Consequently, there is higher potential for a fire accident, also more challenging evacuation process in this stage of the project schedule. Thus, the higher risks are reported for stage 4 by the model. Regarding the last stages of the project in Fig. 9(a), it is illustrated that risk of fire occurrence has reduced due to the fact that fewer job tasks, consequently less equipment, are scheduled to be active in these stages. This trend is similar for evacuation performance safety risk, but as numerous structural and non-structural components are constructed inside the site in the last stages, movement through this congested environment is difficult and more risks would be associated with evacuation from this area, even for a few evacuees. Hence, reduction in evacuation risk is not as much as fire risk. Fig. 9(c), however, shows more convincing values as the overall risk of evacuation in these stages.

Regarding the mentioned risk histories, the overall evacuation risk can be considered as an additional factor in task scheduling and project management planning. Particularly, considering the fluctuations in stages 4 to 6, risk levelling (regarding the corresponding tasks) could be effective in improving the project safety.

So far, this section demonstrated the importance of multi-objective evaluation for evacuation of complex sites (Fig. 7(a-c)). Accordingly, a notable variation was found when evacuation was evaluated only by using evacuation time (which is common in the literature on evacuation of complex environments) in comparison to multi-objective evaluation. Nevertheless, the importance of considering congestion level during site evacuation was demonstrated.

Furthermore, the overall risk of evacuation of the project was assessed by the proposed model. Through the traditional approach, the safety management team was faced with an evacuation risk analysis (in the form of Fig. 8(b)) which might not have been able to provide a reliable insight into site safety conditions. Implementing the proposed model resulted in a more realistic evacuation risk analysis, and more reliable decision-making support where the overall risk of fire occurrence and evacuation capability are taken into consideration. The risk assessed via the proposed approach is in the form of Fig. 8(c) where a considerable difference can be seen.

This research study was implemented on a real project in Iran and benefited from real geometric, semantic, and occupational input data which increased the reliability of the final results. Experimental validation of the developed framework was not feasible because conducting evacuation in the event of fire emergency is basically prohibited and using a validated simulation algorithm was the only alternative to test the proposed framework. However, simulation scenarios were enriched with real input data of Jahan Mall project. Therefore, reliability of the achieved results by the proposed framework could be guaranteed.

In the coming section, we present the results of employing the proposed model to investigate the probable effects of evacuation instruction following behavior on the evacuation risks of the project.

5.3. Investigating the evacuation instructions following behavior

During review of the literature, we laterally found out that in many cases, construction workers sometimes do not follow emergency evacuation instructions [2,9]. For instance, some evacuees choose a route to escape within their imagination from the facility, or choose the shortest way to the exit gate (even through the temporary components or narrow spaces) instead of predefined evacuation pathways [2]. This phenomenon could have appeared due to a wide range of issues, such as stressful situations in the event of an emergency, lack of sufficient emergency response training, tendency to some adverse behavior, and changeable location of works [2]. To investigate evacuation of the studied construction site in a situation that evacuees choose their escape routes off the emergency instructions, a few especial scenarios were designed. In these scenarios, evacuees choose the shortest routes to exit gates, instead of predefined emergency routes. Since almost all work zones of the project are active during stage 6, this stage was picked for this investigation. Fig. 10(a1-c2) presents a comparison of performance of instructed and non-instructed evacuation of the studied site. It is obvious that evacuation time is reduced in the overall scheme when the construction site is evacuated through the evacuation instructions (Fig. 10 (a1-a2)). Moreover, this reduction is significant in the cases of zones 4 and 8. The numerical results are also presented in Table 9. Similarly, congestion level was mitigated throughout the site in the instructed evacuation scenario (Fig. 10(b1-b2)), particularly in the case of zone 4 in

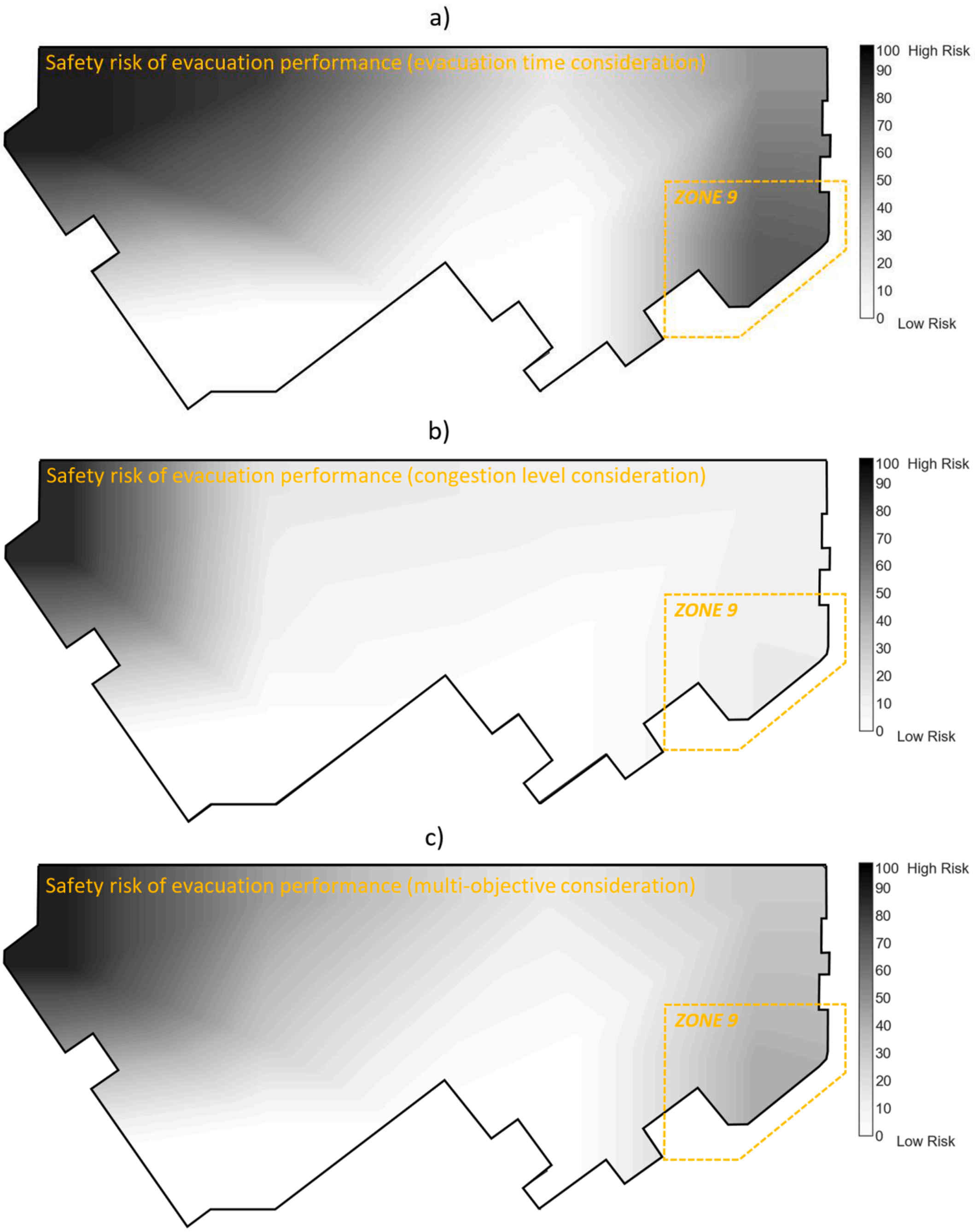


Fig. 7. Evacuation evaluation within the criteria of success; a) evacuation time; b) congestion level; and c) multi-objective consideration. Note: Zones with risk value zero refer to those who are not active at this stage of the project (stage number two).

Table 7
Safety risk values for performance of site evacuation in project stage 2.

Work Zone	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9
TET*	88.93	79.47	48.55	0.00	15.06	0.00	0.00	49.73	63.34
Congestion level	85.34	15.28	9.65	0.00	11.89	0.00	0.00	10.01	13.21
Multi-objective consideration	87.14	47.38	29.10	0.00	13.48	0.00	0.00	29.87	38.28

* Total Evacuation Time

which congestion level has dropped considerably. A probable explanation may be found in instructed scenarios where evacuees are forced to move through predefined pathways and orderly enter exit gates, while in the non-instructed scenario, evacuees run from any direction through the exit gates leading to congested traffic flow. Kneidl, et al. [66], during a study on pedestrians' navigation inside a complex environment, observed a similar phenomenon. They observed higher levels of crowd congestion in the scenarios that no navigation through the destination was applied for the pedestrians. This risky issue is also responsible for longer evacuation time in this scenario. Moreover, in the non-instructed

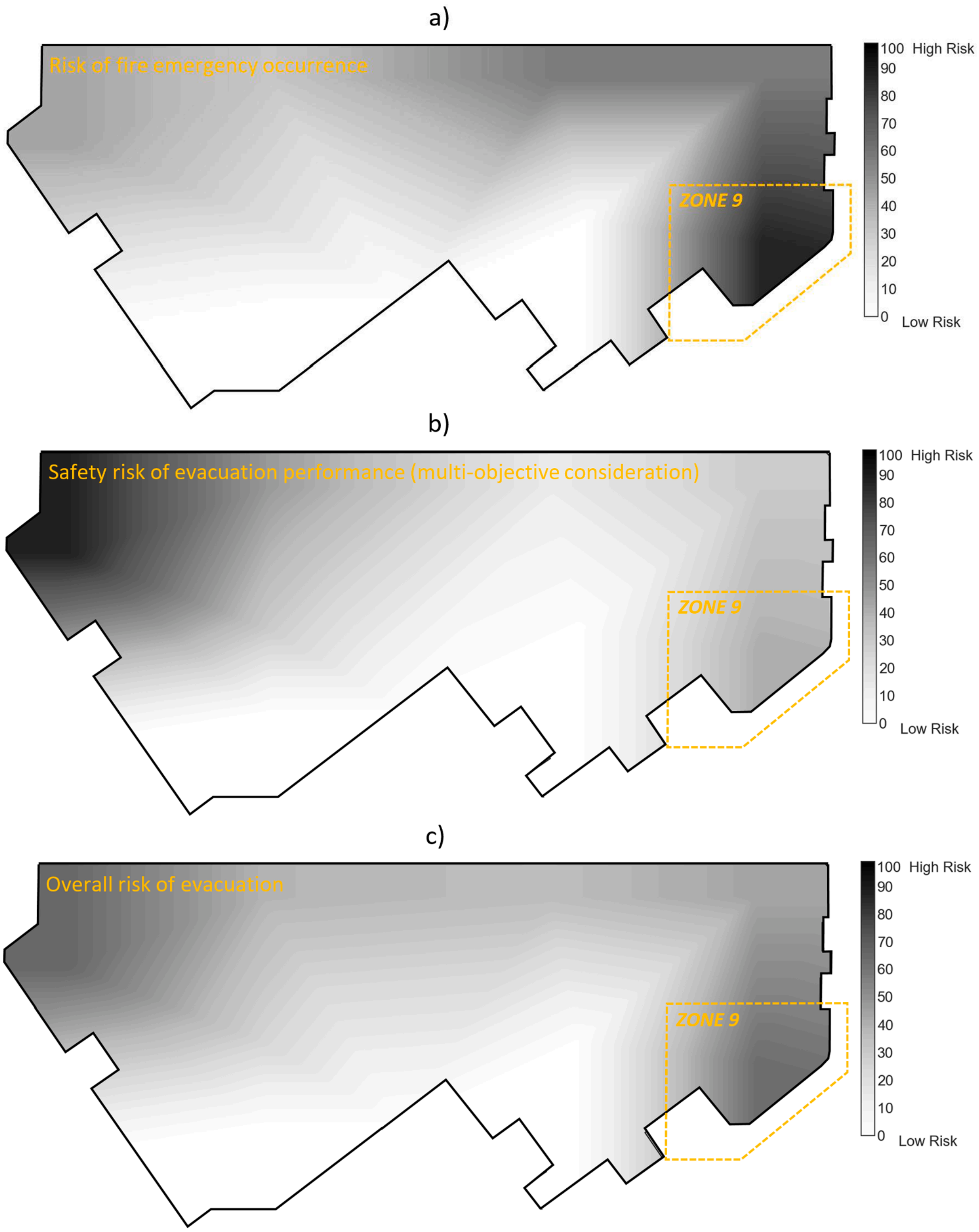


Fig. 8. Evacuation risk analysis for project stage 2; a) fire risk map; b) risk map of ability to successfully evacuate; and c) overall evacuation risk map.

Table 8
Risk values for fire emergency and consequent site evacuation for project stage 2.

Risk Type	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9
Risk of fire occurrence	43.89	31.47	20.82	0.00	57.85	0.00	0.00	57.85	86.98
Evacuation performance risk*	87.14	47.38	29.10	0.00	13.48	0.00	0.00	29.87	38.28
Overall risk of evacuation	65.52	39.43	24.96	0.00	35.67	0.00	0.00	43.86	62.63

* Multi-objectively evaluated.

scenarios evacuees might be affected by other types of risks (such as moving through slippery surfaces, falling from hazardous spots, and being exposed to dangerous temporary stuff) addressing which is not in the scope of this study.

Finally, in the multi-objective evacuation evaluation, when evacuation time and congestion level were simultaneously considered to evaluate safety of evacuation, it was demonstrated that evacuation of the studied site was better performed when personnel followed emergency instructions (Fig. 10(c1-c2)).

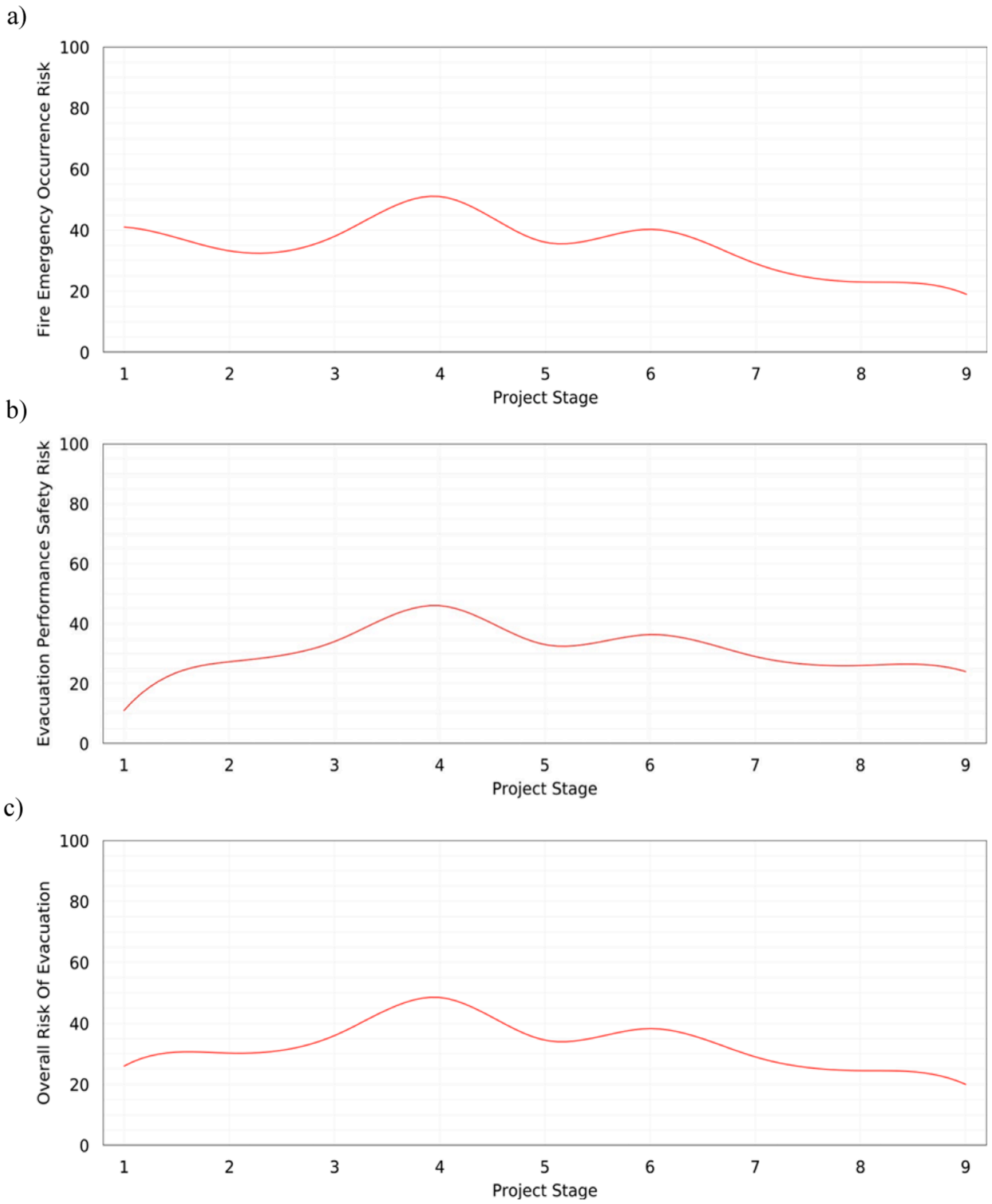


Fig. 9. The history of: a) fire occurrence risk; b) evacuation performance risk; and c) overall evacuation risk over the project execution time.

6. Discussion and future works

Implementing the model on the project provided a realistic perspective of safety conditions of the site for the project management team. In this regard, the introduced overall evacuation risk for the studied project was determined which demonstrated the potential for fire accidents inside the site, and safety of evacuating the site as a response to that fire emergency through an integrated approach. SFM simulator engine, however, helped us to obtain a reliable multi-objective evaluation for the evacuation process of such complex environments. This was not feasible without adopting the introduced parallel computing approach and automatic scenarios re-setup feature of the proposed framework. In addition, the significant effect of following emergency instructions behavior on the project's evacuation performance was revealed. Accordingly, safety management team was highly encouraged to hold extra safety training sessions for the personnel.

Aiming to guarantee the reliability of results, this paper adopted the principals of the methodology of lead papers in this context such as Farina, et al. [67], Johansson, et al. [52], Shuaib [20], and Hou, et al. [68]. The utilized sub-models, however, were picked from experimental validated models including SFM model by Helbing and Molnar [16], Crowd danger model by Feliciani and Nishinari [8], and fire QRA model by Rew and Daycock [45]. Further, consistency of the results of this study with similar credible studies such as Frantzich [6], Kneidl, et al. [66], and El Meouche, et al. [32] demonstrated the reliability of the final results. The developed model was enriched with real-world input data from Jahan Mall project in Iran which increased the practicability of the outcomes of this study. The predefined values, also, were picked from robust sources such as *SFPE handbook of fire protection engineering* [59]. Finally, advantage of the proposed framework in site safety analysis was revealed compared to the traditional approach.

This research study was conducted under some assumptions and

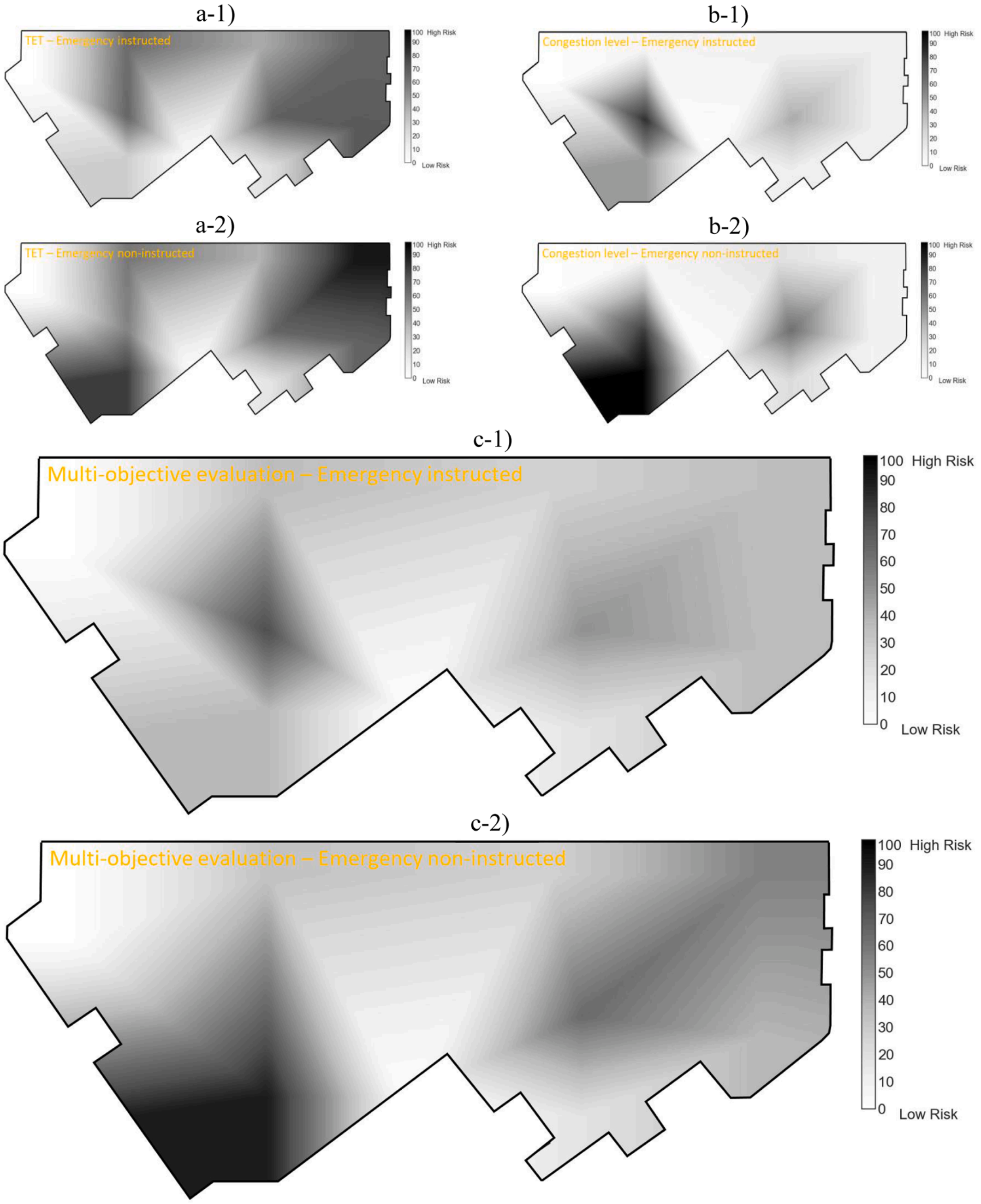


Fig. 10. Simulation results for instructed evacuation scenario (a1, b1, c1) and non-instructed scenario (a2, b2, c2); comparison of a1-a2) evacuation time; b1-b2) congestion level; and c1-c2) multi-objective evaluation.

Table 9
Comparison of assessed risks for instructed and non-instructed evacuation scenarios in project stage 6.

Risk/Objective Type	Evacuation Instructions	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9
Evacuation performance (TET*)	Instructed	0.00	63.69	65.86	28.19	41.80	67.92	20.97	66.29	70.50
	Non-instructed	0.00	59.57	55.43	79.55	39.51	66.14	18.57	92.00	66.98
Evacuation performance (congestion level)	Instructed	0.00	8.81	83.87	47.34	10.21	42.33	12.94	11.79	11.17
	Non-instructed	0.00	7.43	80.04	100.00	14.03	52.07	16.39	9.20	9.52
Evacuation performance (multi-objective)	Instructed	0.00	36.25	74.87	37.77	26.00	55.13	16.96	39.04	40.84
	Non-instructed	0.00	33.50	67.74	89.78	26.77	59.11	17.48	50.60	38.25
Risk of fire occurrence	Instructed	0.00	12.87	51.21	80.09	12.87	52.96	38.95	62.20	51.21
	Non-instructed	0.00	12.87	51.21	80.09	12.87	52.96	38.95	62.20	51.21
Overall risk of evacuation	Instructed	0.00	24.56	63.04	58.93	19.44	54.05	27.96	50.62	46.03
	Non-instructed	0.00	23.19	59.47	84.93	19.82	56.03	28.22	56.40	44.73

[*] Total Evacuation Time.

limitations which relaxing any of them can be a potential subject for future studies. First, the developed framework is prone to human error, and reliability of the achieved results depends on the accuracy of the input materials. Second, the case study of this paper was limited to the grand floor of the studied project. So, the evacuation process in this study was not affected by the merging behavior of evacuees from other floors. Third, the project's site layout was partitioned in nine zones with particular profiles. Change in the number and the form of zones could affect the evacuation process as well as the site analysis. Therefore, in practice, site safety analysis through the proposed framework is sensitive to the site management strategy by the project management team. Fourth, although in this study the emergency evacuation is simulated through an experimental validated model, labors' maneuvering during a real emergency situation may be different with the simulation in a few cases. However, conducting evacuation in presence of fire threat is basically prohibited and simulation of emergency situations is the alternative solution.

According to the final achieved results, the safety management team was provided with three proposals to regulate some high-risk stages of the project: i) risk levelling regarding the corresponding tasks giving priority to regulating the risks associated with stage 4, ii) re-planning parallel activities with consideration of avoiding severe concentration of allocated work force, and iii) assigning extra emergency facilities for evacuation of some determined high-risk zones. Finding optimum values for the mentioned tactics could itself be a potential subject for future research work.

7. Conclusion

Conducting a reliable risk assessment for construction projects might be a challenging issue due to the changeable nature of these complex environments. This study developed a model to analyze the risk of fire emergency occurrence, and risks which are associated with evacuation performance (in response to that emergency) through an integrated approach in complex construction sites. To analyze the evacuation scenarios more realistically, we utilized a microscopic simulation model, Social Force Model (SFM). Using SFM for simulating the evacuation of complex construction sites was not adequately addressed in the literature. Microscopically simulating the evacuation scenarios for all workdays of the studied complex project required high computation efforts. To tackle this computation challenge, a parallel computing technique was coupled with SFM simulation engine. In the proposed framework, based on the rich facility's information that 4D-BIM provided, a QRA model quantified risk of fire occurrence, and a simulation engine evaluated evacuation performance considering the safety metrics of evacuation time and congestion level. For the QRA process, it was assumed that the equipment which were involved in various job tasks are considered as the main ignition sources. The developed model tested on the post-structural phase of a real mega project. Finally, we compared the results of evacuation risk assessment considering a) only evacuation performance risks, and b) resultant risk of fire emergency occurrence and evacuation performance risks. More convincing risk values were determined when potential for emergency occurrence, and potential for a proper evacuation were considered through an integrated approach. In addition, the effects of emergency instruction following behavior on performance of evacuation of the studied site was investigated and the simulations revealed that both evacuation time and congestion level significantly increased when the site was evacuated non-instructed. Implementing this model on a real complex construction site supported the ability of the model to provide more reliable insight into the safety condition of complicated projects. The results also provided the project managers with a reliable safety decision-making support.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aei.2021.101378.

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