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Simulation of labor evacuation: The case of housing construction projects

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Abstract Construction sites occupy of the labors who are engaged in many different activities that can expose them to dangerous conditions. During emergencies and extreme events of natural or manmade origin in construction sites, saving labors lives is the primary objective. Therefore, the contractors are required to establish effective emergency plans which have to be improved to aid for rapid egress from construction sites. To support emergency evacuation planning, it is critical to estimate labor evacuation times during project execution. This paper presents a framework that utilizes building information modeling (BIM) and computer simulation to plan the evacuation of labors in construction sites during project execution and to visualize evacuation times of labors at emergency conditions at any time from project duration. The proposed framework utilizes MassMotion software as the simulation platform that enables predicting the labor evacuation times under various conditions. In addition, the evacuation time calculated from computer simulation is used to develop and evaluate the plan. A case study is worked out to demonstrate a simulation of emergency evacuation from a housing building during its construction to demonstrate the use of the proposed framework. Finally, the paper presents the simulation results of labors evacuation in the housing building construction sites.

Introduction

Construction sites are subject to a wide way of emergencies and hazards. Structural collapse, fire, act of violence, explosion, earthquakes, and unexpected weather condition are among the many kinds of emergencies that may require a construction site to be safety evacuated. As such they may be seen as an example of a complex environment. Construction sites have the potential to accommodate hundreds of occupants, especially in high-rise building projects where contractors and workers carry out their activities. The occupational safety and Health Administration (OSHA) and other agencies require written emergency plan and safe means of egress on

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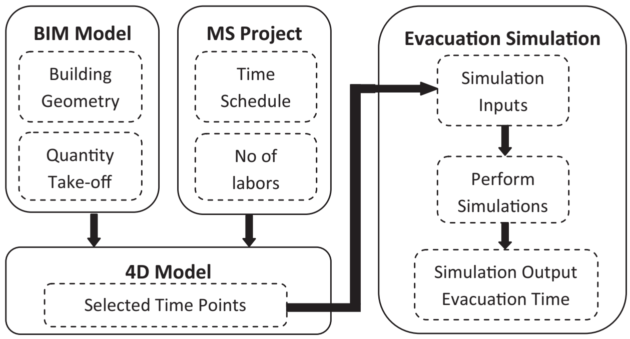

Fig. 1 Main components of evacuation framework.

construction sites. Accordingly, the contractors need to apply an effective emergency plan to prevent emergencies from occurring on construction sites.

However, many researchers have focused on the evacuation of the large population in public environments, such as malls, stadiums, airports, libraries, and metro station [1–4]. These environments have fixed spatial and occupants. Construction site environment changes continuously that which means the number of occupants, spaces and evacuation routes change from one day to another. Evacuation conditions for occupants that work in construction sites could be very different from the conditions that can be expected in public buildings [5]. Although evacuation models have been used in studying emergency evacuation for decades, little research has been done on construction sites. This paper presents a framework which helps the contractors to develop effective rescue and evacuation plan when an emergency or disaster happens and investigate the emergency evacuation time of occupants over the different points of time during project execution.

In this paper, the methodology contained three steps. The initial step involved an exhaustive review of the literature on emergency evacuation models. In the next step, a framework is developed using the integration of Building Information Modeling and computer simulation. The model uses Building Information Modeling (BIM) to build an adaptable 3D virtual reality environment. Computer simulation is adopted using agent-based simulation to model the behavior of labors in evacuation situations. The proposed simulation model utilizes MassMotion software, as a simulation engine to implement agent-based simulation. Finally a case study is worked out to illustrate the use of the proposed framework.

The remainder of the paper is organized as follows: Sectio n 'Emergency evacuation models' introduces related work in the field of evacuation simulation. Section 'Proposed framework' describes the proposed framework evacuation simulation using building information model and MassMotion software. Section 'Case study: evacuation simulation' provides the evacuation simulation of a case study: finally, Section 'Results and discussion' represents results and discussion.

Emergency evacuation models

Modeling of occupants' evacuation simulation from a building has been studied over the past years. Many evacuation simulation models have been established and applied to simulate occupant evacuation and evaluate the evacuation efficiency for buildings. These models can be classified in two main approaches: the macroscopic approach and the microscopic approach [6]. The first model focuses on crowd behavior as a whole and ignores the local dynamics of individuals and interactions between pedestrians. In the second model, the pedestrians are considered individually focusing on the local interactions of the pedestrians with their immediate environ-

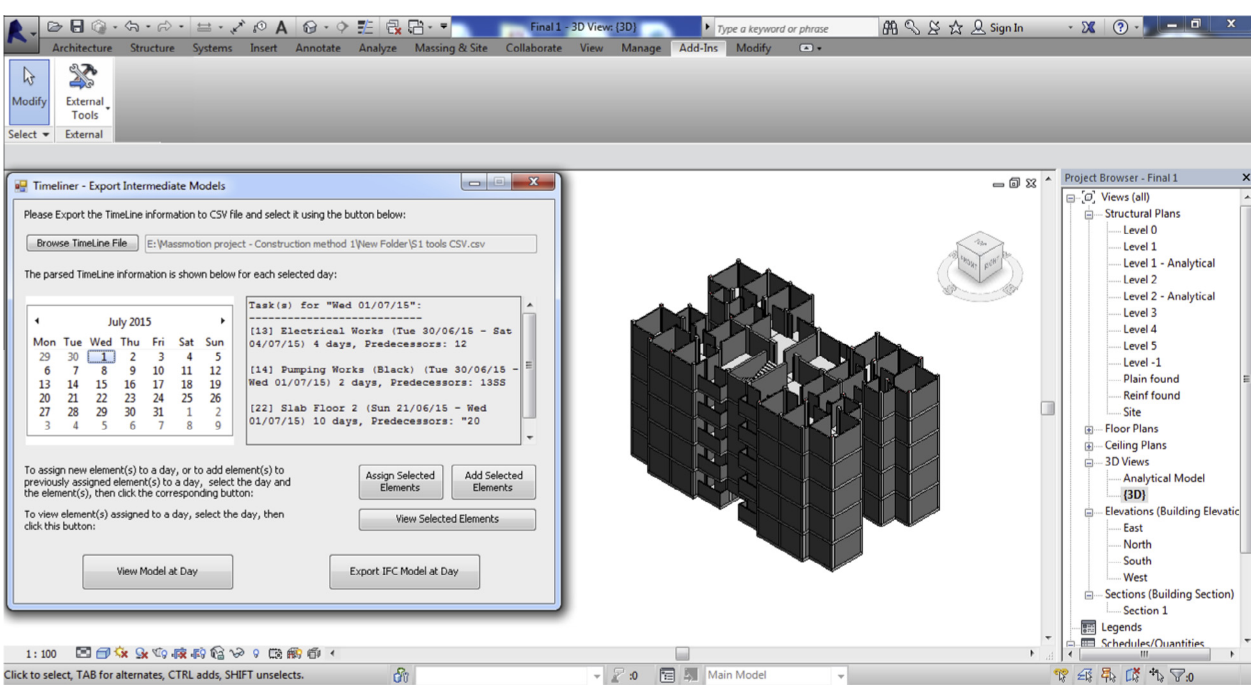

Fig. 2 Additional tool image in Revit Software.

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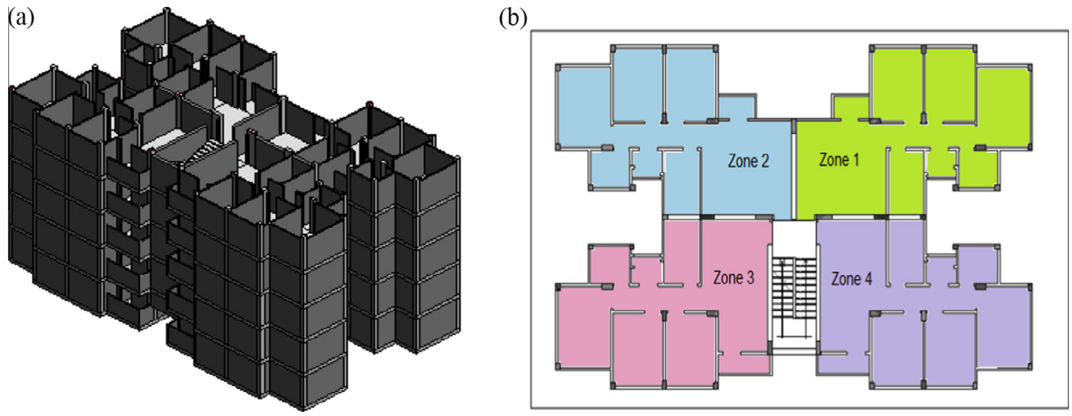

Fig. 3 (a) Building layout and (b) building zones for each floor.

Table 1 Number of labor and location for selected time points.

Cases	Activities	Floor	Location zone	No of labor	Total labor
Case 1	Slab Works	1	1, 2, 3, 4	24	24
Case 2	Electrical Works	1	3	8	26
	Column Works	3	1, 2, 3, 4	18	
Case 3	Tiling Works	1	3, 4	12	44
	Electrical Works	2	2	8	
	Pumping Works	2	1, 2	6	
	Column Works	4	1, 2, 3, 4	18	
Case 4	Doors and Windows Installation	1	3, 4	14	62
	Plastering Works	2	4	14	
	Block Works	3	1	10	
	Slab Works	4	1, 2, 3, 4	24	
Case 5	Tiling Works	2	3, 4	12	38
	Electrical Works	3	3	8	
	Column Works	5	1, 2, 3, 4	18	
Case 6	Doors and Windows Installation	2	1, 2	14	60
	Tiling Works	3	1	12	
	Block Works	4	2	10	
	Slab Works	5	1, 2, 3, 4	24	
Case 7	Doors and Windows Installation	3	3, 4	14	38
	Plastering Works	4	4	14	
	Block Works	5	1	10	
Case 8	Painting Works	4	2	10	24
	Plastering Works	5	1	14	

ment. Several microscopic pedestrian models have been developed for simulation. These models can be classified according to how they model the individual behaviors: Cellular automata model [7–9], force-based models [10,11], and agent-based model [12,13].

In recent years, a variety of researches focus on the micro models and many efforts have been conducted to modeling the different aspects of evacuation simulation. Tan et al. [14] performed agent-based simulation of building evacuation using a grid graph-based model. Said et al. [15] proposed conceptual agent-based framework for modeling labor evacuation in high rise building construction sites. Wang et al. [16] introduced the use of Cell-DEVS theory based on building information model for the evacuation of the multi floor building. In Rüppel and Abolghasemzadeh [17], a BIM-ISEE (Immersive Safety Engineering Environment) was developed, focused on the realistic virtualization in their immersive environment for integrating fire and evacuation simulation with BIM tools. Wang et al. [18] introduced a BIM based virtual environment supported by virtual reality (VR) and a serious game engine to address several key issues for building emergency management and to provide real-time fire evacuation guidance. Shi et al. [19] constructed agent based evacuation model based on integration 3D GIS and BIM platform. Liu et al. [20] developed a framework to build a human library for emergency evacuation through a BIM based serious game environment.

Evacuation simulation models can be used to predict and analyze the performance of the evacuation process in a specific

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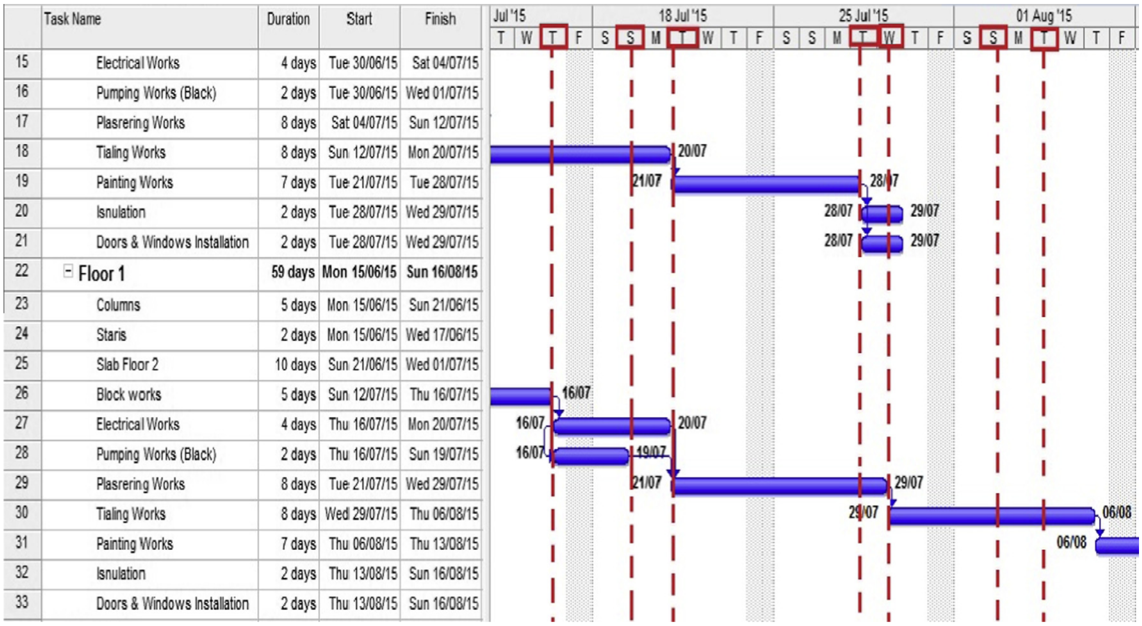

Fig. 4 Selected point in time for evacuation during project execution.

building and thus become an important tool for doing the building evacuation analysis [21]. Moreover, they help decision-making when creating evacuation plans. A number of specialist simulation software packages have been widely used for evacuation simulation. The results of the simulation models presented in this study have been calculated using MassMotion modeling software [22]. MassMotion simulation software is an agent based software tool used to create a professional virtual prototyping environment, and it also analyzes and represents the behavior of individual pedestrians in their interactions with other people [23]. The movement of individual agents in MassMotion is based on a social forces algorithm modified for MassMotion [11]. The social forces model represents individuals as objects which have a number of forces acting upon them including goal, obstacle, and neighbor forces [24].

Proposed framework

Building information modeling is defined by the United States National BIM Standard as “a digital representation of physical and functional characteristics of a facility” [25]. Recently, application of BIM technology on construction management is very important because stakeholders in different stages of building construction projects require saving time, cost and working collaboratively. On the other hand, Industry Foundation Classes (IFCs) are the standard data formats for BIMs [26]. IFC has provided an interoperability solution between different software applications. This format has established, international standard to import and export building objects and their properties. Autodesk Structure Revit, a widely used BIM platform, is used as the BIM software in the proposed framework. Revit provides an application programming interface (API) to interact directly and facilitate data transfer to other different applications. Revit API supports the object-oriented programming language. The API allows software developers to add customized tool bars, functionality, and connectivity to external sources using software programs written in C# language. Our modeling framework applies this methodology to import data from project planning packages, such as MS Project to Revit. In addition, export data from Revit to external platform evacuation simulation such as MassMotion software.

The proposed framework consists of four main steps: BIM Model, MS Project, 4D Model, and Evacuation Simulation Model. Fig. 1 depicts a schematic diagram for the proposed framework that shows the interaction between its components. At the beginning of modeling determine the dimensions for the building and draw the building geometry in Revit with important components such as columns, slabs, walls, stairs, and rooms. The second step is creating construction planning for this project using MS Project software. Construction planning involves scheduling and sequencing activities in time and space with taking into account resources and other concerns in the process. When the building project plan is complete, the user can export the project plan, including activities and relationships from MS Project to Comma Separated Value (CSV) file format. CSV is a text-based file format and it is used to communicate with the project planning packages and the IFC class in Revit. The third step of modeling is to link building elements from the 3D BIM model with time schedule to produce the 4D model, and the user selects the element from the Revit visualization screen via mouse clicks. The selected elements are highlighted with blue color. Once all the building elements related to activities associated with a specific day, are highlighted, the specific day has to be selected via the mouse as well. The selected building elements and the associated day are linked as soon as the user presses the Assign Selected Element button. The tool of the Revit software enables you to view the work tasks of the schedule along with the visual of the 3D model at any day through View Model button. When the linking process for all elements is complete, the user exports the element at any day of schedule to Industry Foundation Classes (IFC) file format through Export IFC Model button.

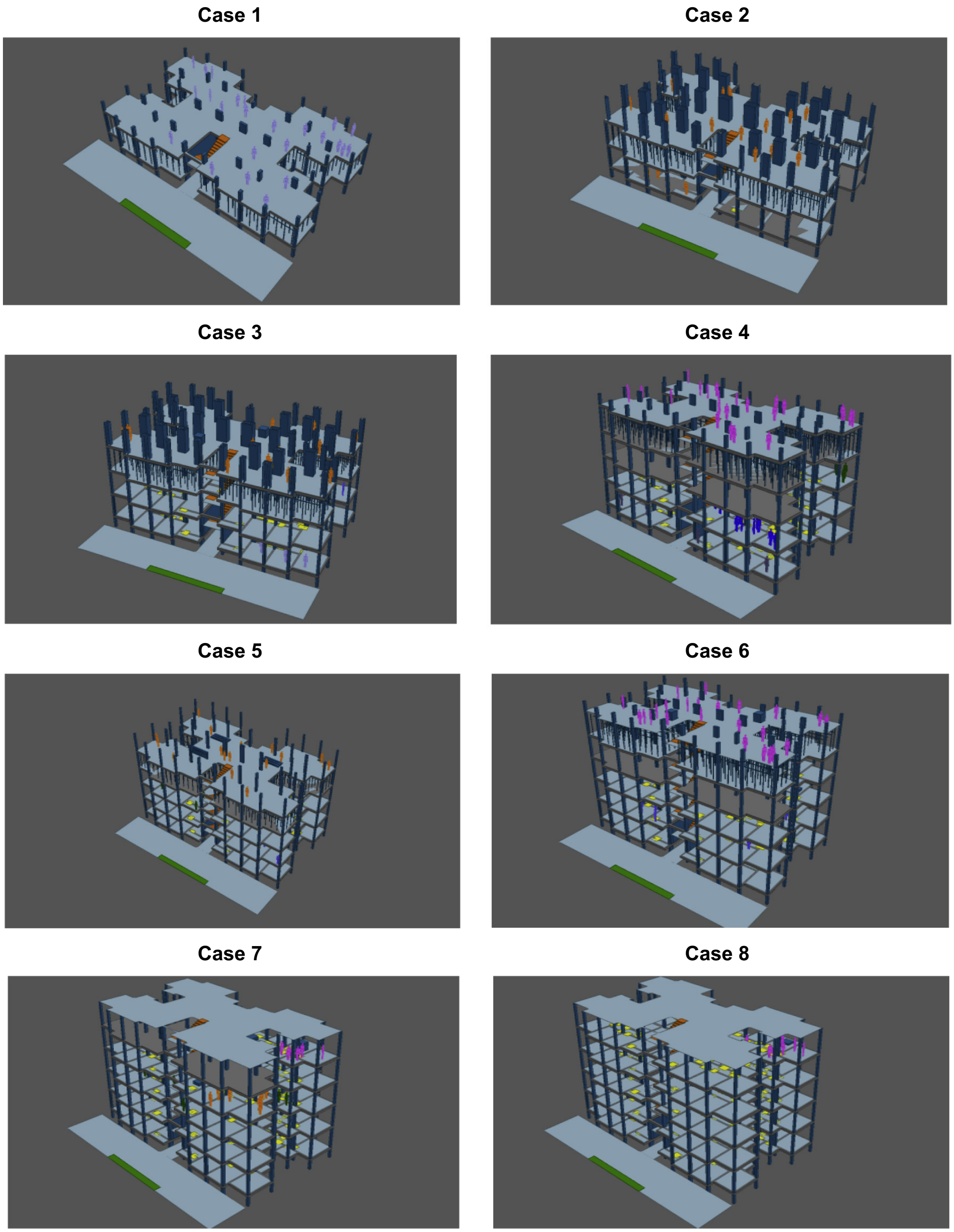

Fig. 5 Considered eight cases at different time points.

The tools is a plug-in based on the API of Revit Structure 2014 programmed by Visual C# will trigger two processes. Firstly, Schedule project data which store activities names, durations, and early times (start and finish) will be imported into CSV file from MS project and assign each construction activity with related building element for each day at the project duration. Secondly, the BIM model data at any day will be exported in Industry Foundation Classes (IFCs) file format and stored in an external folder for simulation. Fig. 2 presents image for the additional tool in Revit that was used to produce 4D model.

The fourth step of the modeling framework is evacuation simulation model. The proposed simulation model utilizes MassMotion, as a simulation engine. The user imports the IFC file and defined all geometry building that scheduled until analysis day in the MassMotion simulation software. The

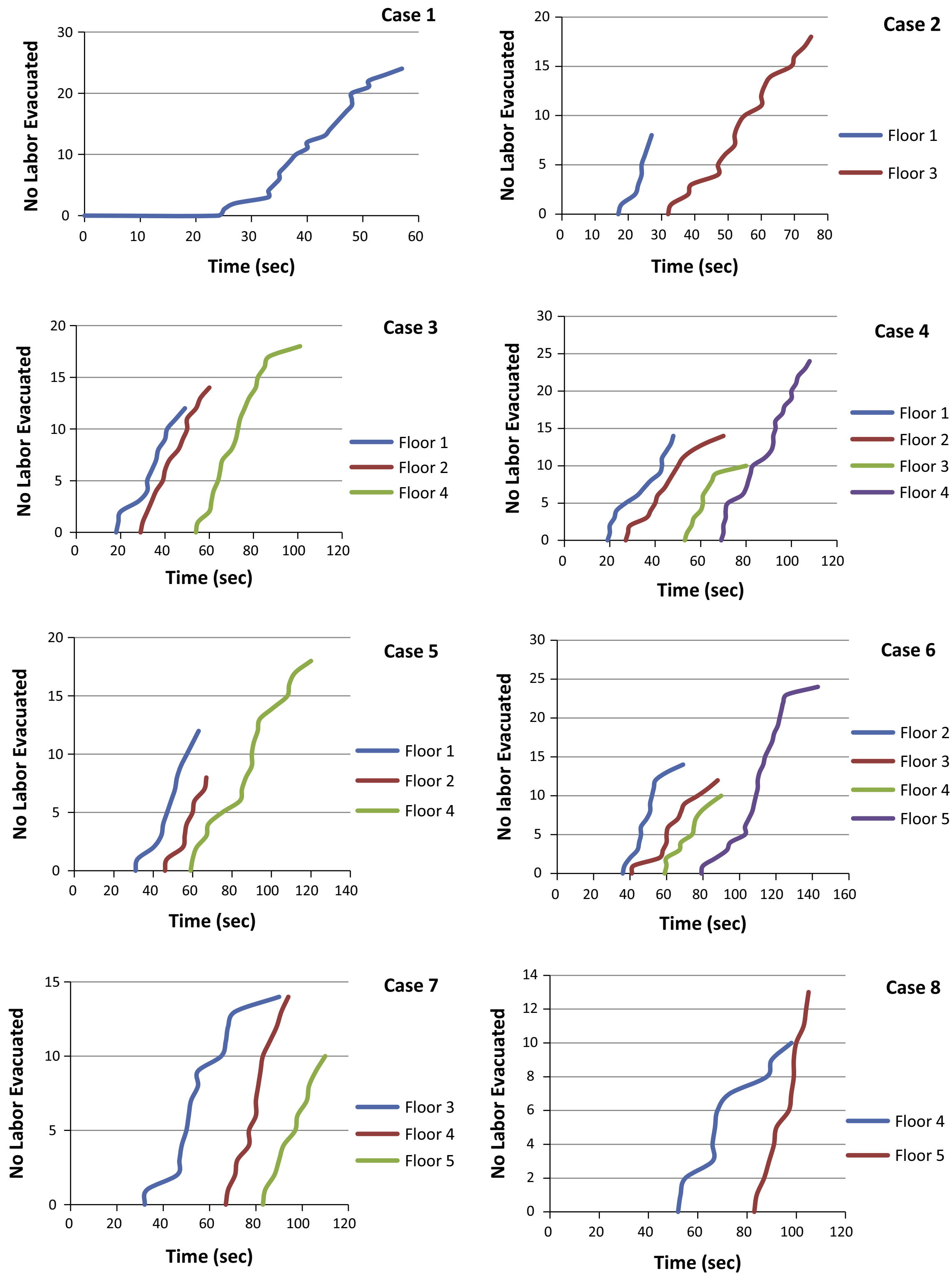

Fig. 6 Cumulative number of labor evacuated in different cases.

simulation input data include number of labors for each floor, locations, labor evacuation speed, and labor profile. Once the simulation input is carried out, the simulation model launches MassMotion to generate the labor agents in the specified location according to different works for the project. MassMotion estimates the labor evacuation times which are used to develop emergency plans.

Case study: evacuation simulation

Egyptian social housing projects are one of the most important housing projects that are directed to serve low-income people in Egypt. These projects are repetitive and typical units; the number of floors is five floors since this type of building is

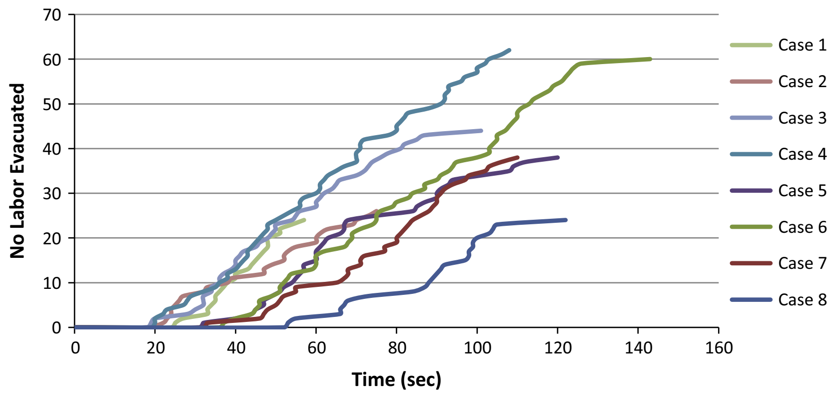

Fig. 7 Required evacuation time for all cases.

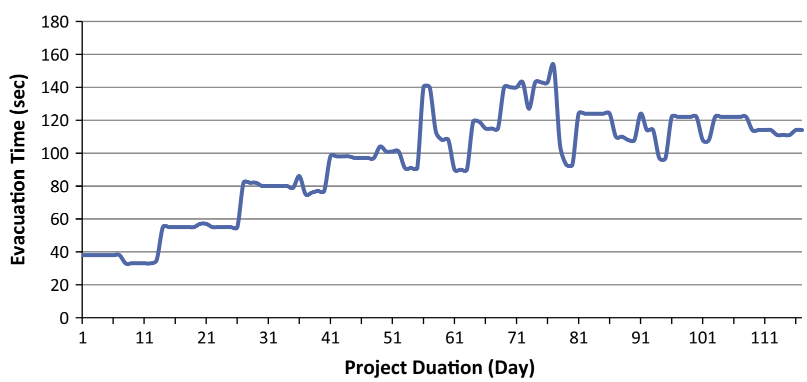

Fig. 8 Different evacuation time during the project execution.

not equipped with elevators. The height of each floor is 3 m. All the floors have the same layout and each comprises 4 units, which is shown in Fig. 3(a). The area of each floor is approximately 360 square meters and it is divided into four zones with one main entrance which is also used as an exit which is shown in Fig. 3(b). The width of the stair in the building is 1.0 m. Further, the total duration of construction project execution depending on time activities is 154 days and time points were selected from the beginning of the fifth week for the project to perform the evacuation.

The case study is executed in two stages. The first stage starts through modeling BIM in Revit and time schedule in MS Project for the project. Using additional tool in Revit, the linkage process between building elements and activities is performed. The data associated with each day in the project are exported through the API and C# tool to IFC file format and then saved in an external file. On the other hand, Forty-two time points from the project schedule for labor evacuation were chosen during project execution according to change in assigned resources to activities and activities location. These time points have been chosen at start times and finish times for activities to show the greatest various emergency situations with the progress of work in the project as shown in Fig. 4. The second stage starts through MassMotion modeling which involves building up the 3D geometry and imported the IFC format file for the selected date. Other required inputs include the number of labor agents that generate randomly for every activity in its location according to schedule time as shown in Table 1. The labors required for each activity were calculated based on the quantity of work and productivity of labor.

The evacuation model is established taking into consideration continuous space, discrete time and modified social force considerations. Each of the individual labor agent profiles in the MassMotion simulation is assigned with the agent speeds which are normally distributed in a range from 0.65 to 2.05 m/s with average 1.3 m/s and a standard deviation of 0.25 m/s from their current locations different floor to the assembly point. The parameters for the stair are assumed to be the same as the default values in MassMotion. Agent speeds on stairs are prescribed within MassMotion based on Fruin's speed profiles [27]. Agent size is included in the MassMotion calculations. The default value for the body radius is 0.25 m. In all cases, it is assumed that the labors are familiar with the building construction site.

In this paper, we review eight cases only from forty-two time points selected during the project execution to estimate the evacuation time for these time points from the start of the alarm until the last labor evacuated. Then, a graphical report is generated to show the different evacuation times for all time points during the project duration. Fig. 5 represents cases that are selected for the simulation in performing evacuation simulation. In all various images, it can be noticed that there are no walls to show the labor movement.

Results and discussion

Evacuation time is the most commonly used measure of effectiveness for evacuation planning. Furthermore, the evacuation process for each case can be described by evacuation curves, which represent the cumulative number of labors evacuated from the evacuation area as a function of time. Fig. 6 shows the evacuation curves associated with each case when the labors were randomly positioned according to specific locations. For example, in case 2 the evacuation curves represent the labor evacuated in the first and third floors. It can be seen that the evacuation time is increasing with project progress. In addition, the labor evacuations from upper floors have a great influence on overall evacuation time for each case since it enlarges evacuation time.

All the figures in the previous section show the flow of the labors in each case without any pre-movement time. The resulting graphs were plotted from the start of the alarm until the last labor evacuated. Fig. 7 illustrates the comparison of cumulative evacuation time of labors from building different times eight cases during the project. The results indicated to the largest evacuation time in case 6 with 143 s and the case 1 has the lowest value. It was also obvious that the concrete activities affect the evacuation time because the large number of labors in these activities reduces the labor movement during the evacuation process.

Fig. 8 represents the evacuation time of labors from the building construction site at different times that were selected during the project duration. The simulation results indicated small evacuation time at the beginning of the project because of the small number of activities, labors and floors. On the other hand, the evacuation time increases with the activities and labor density in the duration middle of the project. The results of evacuation simulation determine the activities for the project that significantly affect evacuation time. Therefore, the change of sequence of these activities leads to reduce the evacuation time during the project duration. And also, more attention should be paid for safety aspects when preparing the emergency plan at these activities. The benefits of the model presented here include the ability to perform the evacuation process to estimate the time required to enable labors reach the assembly point outside the building. The simulation enables to detect congestions through the 3D visual demonstration during the evacuation. In addition, contractors using the model can test emergency evacuation plans prior to construction to identify whether the planned construction method is appropriate to be adopted. The research provides additional tool to produce 4D model.

Conclusions

This paper presented the proposed framework for the emergency evacuation model of building construction sites. This model was used to calculate the total evacuation time on each floor and the stairs until the assembly point outside the location and investigate the possibility for construction workers to safely evacuate over the duration of the project. In addition, the simulation analysis highlights potential areas of localized congestion through a visual representation of labor movements during the evacuation process. The results help the contractor to develop effective emergency plans and find a way for existing plans improvement through determining the activities for the project that affect evacuation time.

The proposed research has a number of limitations. First, the model is not designed for the outdoor labor evacuation situation. Second, the evacuation considers only labors in construction sites. However, in the real-world, there are other numbers of construction site staff that need to be considered as well. This research can be extended in the future to consider a number of building constructions which contain many of assembly points in the project for a more realistic simulation. Further, more flexibility can be added by considering more construction methods that include different sequence of activities during project execution.

References

[1] Syed Ashraf Tashrifullahi, Mohammad A. Hassanain, A simulation model for emergency evacuation time of a library facility using EVACNET4, Struct. Surv. 31 (2) (2013) 75–92.

[2] Ze-min Jiang, Pei-ong Zhang, Rong-xue Shang, Xiang-liang Tian, Investigation and simulation on human evacuation behaviour in large hospital building in Shenyang, Proc. Eng. 71 (2014) 101–106.

[3] Ji-hua Hu, Cheng-zhi Zhan, Zhi-feng Cheng, Wang Bo, A research of pedestrian evacuation simulation for BRT station based on fine grid method, Proc. Eng. 52 (2013) 137–144.

[4] Radoje Jevtic, Simulation of evacuation – the case of electrotechnical schoole laboratory part, Facta Universitatis, Series: Working and Living Environmental Protection 2016, pp. 253–260.

[5] Hakan Frantzich, Daniel Nilsson, Evacuation in complex environments – an analysis of evacuation conditions at a tunnel construction site, in: Fourth International Symposium on Tunnel Safety and Security, Frankfurt am Main, Germany, March 17–19, 2010.

[6] Andreas Schadschneider, Wolfram Klingsch, Hubert Klüpfel, Tobias Kretz, Christian Rogsch, et al, Evacuation dynamics: empirical results, modeling and applications, in: Encyclopedia of Complexity and Systems Science, Springer, New York, 2009, pp. 3142–3176.

[7] Nuria Pelechano, Ali Malkawi, Evacuation simulation models: challenges in modeling high rise building evacuation with cellular automata approaches, Autom. Constr. 17 (4) (2008) 377–385.

[8] Carsten Burstedde, Kai Klauck, Andreas Schadschneider, Johannes Zittartz, Simulation of pedestrian dynamics using a two-dimensional cellular automaton, Phys. A: Stat. Mech. Appl. 295 (3) (2001) 507–525.

[9] Ansgar Kirchner, Andreas Schadschneider, Simulation of evacuation processes using a bionics-inspired cellular automaton model for pedestrian dynamics, Phys. A: Stat. Mech. Appl. 312 (1) (2002) 260–276.

[10] Dirk Helbing, Peter Molnar, Social force model for pedestrian dynamics, Phys. Rev. E 51 (5) (1995) 4282.

[11] Dirk Helbing, Illés Farkas, Tamas Vicsek, Simulating dynamical features of escape panic, Nature 407 (2000) 487–490.

[12] M.C. Toyama, A.L.C. Bazzan, R. Da Silva, An agent-based simulation of pedestrian dynamics: from lane formation to auditorium evacuation, in: Proceedings of the Fifth International Joint Conference on Autonomous Agents and Multiagent Systems, Hakodate, Japan, 8–12 May 2006, pp. 108–110.

[13] Nicholas R. Jennings, An agent-based approach for building complex software systems, Commun. ACM 44.4 (2001) 35–41.

[14] Lu Tan, Hui Lin, Mingyuan Hu, Weitao Che, Agent-based simulation of building evacuation using a grid graph-based model, IOP Conference Series: Earth and Environmental Science, vol. 18, no. 1, IOP Publishing, 2014.

[15] Hisham Said, Amr Kandil, Hubo Cai, Agent-based simulation of labour emergency evacuation in high-rise building

Please cite this article in press as: M. Marzouk, I. Al Daoor, Simulation of labor evacuation: The case of housing construction projects, HBRC Journal (2016), http://dx.doi.org/10.1016/j.hbrcj.2016.07.001

construction sites, in: Construction Research Congress 2012@ sConstruction Challenges in a Flat World, ASCE, 2012.

[16] Sixuan Wang, Michael Van Schyndel, Gabriel Wainer, Vinu Subashini Rajus, Robert Woodbury, Devs-based building information modeling and simulation for emergency evacuation, in: Simulation Conference (WSC), Proceedings of the 2012 Winter, IEEE, 2012.

[17] U. Rüppel, P. Abolghasemzadeh, BIM-based immersive evacuation simulations, in: 18th International Conference on the Application of Computer Science and Mathematics in Architecture and Civil Engineering, 2009.

[18] Bin Wang, Haijiang Li, Yacine Rezgui, Alex Bradley, Hoang N. Ong, BIM based virtual environment for fire emergency evacuation, Sci. World J. (2014).

[19] Jianyong Shi, Pai Liu, An agent-based evacuation model to support fire safety design based on an integrated 3D GIS and BIM Platform, Comput. Civ. Build. Eng. (2014) 1893–1900.

[20] Rui Liu, Jing Du, Raja R.A. Issa, Human library for emergency evacuation in BIM-based serious game environment, in: Computing in Civil and Building Engineering, ASCE, Reston, VA, 2014, pp. 544–551.

[21] Tzu-Sheng Shen, ESM: a building evacuation simulation model, Build. Environ. 40 (5) (2005) 671–680.

[22] Oasys MassMotion Software, <http://www.oasys-software.com/products/engineering/massmotion.html>.

[23] E. Morrow, MassMotion: simulating human behaviour to inform design for optimal performance, Arup J. (2010) 38–40.

[24] Eric Rivers, Carla Jaynes, Amanda Kimball, Erin Morrow, Micah Zarnke, Using case study data to validate 3D agent-based simulation tool for egress modeling, in: Fire and Evacuation Modeling Technical Conference, Baltimore, Md, 2011.

[25] National Building Information Model Standard Project Committee, Frequently Asked Questions About the National BIM Standard-United States™, <https://www.nationalbimstandard.org/faqs#faq1> (accessed 20 Jan, 2016).

[26] Laakso Mikael, A.O. Kiviniemi, The IFC standard: a review of history, development, and standardization, information technology, ITcon 17 (2012) 134–161.

[27] John J. Fruin, Pedestrian Planning and Design, Elevator World, Inc., Mobile, Alabama, 1971.

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