



# Planning labor evacuation for construction sites using BIM and agent-based simulation



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## ABSTRACT

This paper presents a framework that aids contractors and safety managers in planning labor evacuation for construction sites using Building Information Modelling (BIM) and computer simulation by modeling the appropriate construction method alternatives. The proposed framework estimates the execution time, total cost, and evacuation time for construction projects, taking safety into consideration. Agent-based simulation is utilized to model the behavior of laborers in evacuation situations. A MassMotion simulation platform is utilized to implement agent-based simulation and to imitate labor behavior during emergency evacuation under various conditions. Ranking and Selection (R&S) statistical procedures are used to determine the best simulated model configuration among the considered four alternatives. Multi Criteria Decision Making (MCDM) is applied to help in selecting the suitable construction method alternative. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is used to identify the best construction method alternative taking into consideration three main criteria which are: construction total cost, execution time, and evacuation time of the labor. The proposed framework is examined within the context of a case study that considers evacuation of labor during the construction of a building in an Egyptian social housing national project.

## 1. Introduction

Construction sites are considered very risky environments that contains a large number of construction labor performing various activities. There are many different circumstances of natural disasters or anthropogenic (human-made) hazards that would cause the evacuation of construction sites, such as fire, structural collapse, gas leaks, earthquakes, explosions, and civil disorders. To reduce potential hazards when emergencies happen in construction sites, it is essential to prepare safety evacuation plans to direct labor to retreat from the hazard location in a rapid and safe manner. According to Occupational Safety and Health Administration (OSHA, 2015) and other agencies, predicting evacuation time required for the labor to vacate is the major objective when preparing the evacuation plan for construction sites. Construction site environment changes continuously which means the number of occupants, spaces and evacuation routes changes 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. Although many evacuation models have been used in studying emergency evacuation for decades, little research has been done for construction sites.

Generally, a number of previous studies were focused on the evacuation issues of the large population in public environment, such as malls, stadiums, airports and multistory buildings. These environments that have fixed spatial and occupants. Besides, the evacuation process was conducted on operation stage of these environments. In addition, while most existing studies aim at an indoor system, emergency evacuation system for outdoor and construction sites environments are also needed. Construction site environment contain many temporary works, its changes continuously that which means the number of occupants, spaces and evacuation routes changes from one day to another. Common problem when established evacuation route in construction site may include obstructed hallways from materials and equipment that can impact the ability to quickly evacuate a construction site. This research proposes a framework that is capable to estimate the evacuation time of labor over the different points of time before project execution. Thus, the proposed model helps the contractors to develop effective evacuation plan when an emergency or disaster happens and using this model can test emergency evacuation plans prior to construction to identify whether the planned construction method is appropriate to be adopted. The proposed framework that integrates Building Information Modeling (BIM) with computer simulation to

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planning emergency labor evacuation on a construction site. Based on agent-based model technology, MassMotion software simulates the labor behavior and movements. The proposed framework estimates the total evacuation time, time of execution, and total cost for a given construction setting.

## 2. Literature review

Nowadays, new technologies and tools are available to manage and plan the emergency evacuation of labor in construction sites. Building Information Modelling (BIM) technology has been introduced to provide comprehensive building information for three-dimension (3D) visualizations of the interior design of the building under study. BIM model produces the 4D model by linking the model elements and time schedules (Eastman et al., 2011). Modeling and Simulation tools are used to gain increased understanding of labor behavior during the emergency. Agent-based modelling tools are used to model the behavior of labor in evacuation situations. It provides a natural description of labor movements and produces realistic simulation. These new technologies increase the accuracy and improve planning of the evacuation processes for construction sites as described in the below subsections.

### 2.1. Building Information Modelling (BIM)

Building Information Modeling (BIM) technology provides a digital representation of the actual physical characteristics of a building. BIM provides a perfect platform for sharing the information among designer, managers, contractors, engineers, and more importantly, the construction industry. BIM can provide information and documents that are related to emergency evacuation and calculate the safety performance and evacuation routes before the project begins. BIM provides accurate building information and exceptional details of the facility. For the last few years, there has been an increasing emphasis within BIM research and evacuation simulation systems. Ruppel et al. (2009) developed a BIM-ISEE (Immersive Safety Engineering Environment) to model emergency situations in buildings and applied the situations to a group of individuals fearing danger. The model integrated fire and evacuation simulation with BIM tools. Wang et al. (2012) developed a model to simulate emergency evacuation based on BIM and Discrete Event Systems Specification (DEVS). The model can be used to analyze bottlenecks and the maximum occupation for determining an optimal evacuation plan. Wang et al. (2014) integrated BIM and a serious game engine to provide real-time fire evacuation guidance. The study introduced a BIM based virtual environment (BIM-VE) to improving building emergency management. Mayer et al. (2014) developed a pedestrian simulation model based on BIM data to identify potential threats in the design phase of a building and evaluate protective measures. This model can utilize information of the BIM model during the operation phase of a building.

### 2.2. Computer simulation

Evacuation simulation is an important tool for analyzing and assessing the safety of labor on a construction site. It can be used for modelling the emergency evacuation to predict and understand the performance of the evacuation process in a specific building (Zheng et al., 2009). The contractors and safety managers can use simulation to estimate evacuation time and find the potential bottleneck a reason the building construction site before the construction has begun. Many researchers have adopted agent-based modelling techniques to use in evacuation simulation. It provides a natural description of labor movement during the emergency evacuation simulation. In addition, agent-based modelling techniques are capable to produce realistic and detailed simulation. Bonabeau (2002) introduced the basic principles and possibilities of agent based simulation and application methods in

evacuation, flow management and diffusion. Klugl and Rindsfuser (2007) studied the crowd movement centered on an agent-based modelling and simulation in the traffic and transportation domain. Pan et al. (2007) studied the human and social behavior during emergency evacuations in buildings through developing a multi-agent simulation framework able to demonstrate different emergent behaviors. Lin et al. (2010) developed an agent-based simulation model for a 2-story office building. The model uses the evacuation data that was collected by video cameras during fire drills in the building. Zaharia et al. (2011) proposed an agent-based model for the simulation of an emergency route by taking into account the problem of uncharacteristic actions of people under distress conditions caused by a disaster. Bernardini et al. (2014) proposed an evacuation simulation model using agent-based modelling techniques and through analysis of videotapes recording real events. His study included modifying the social force model in order to describe typical behaviors. Tan et al. (2015) presented an agent-based evacuation model in which the evacuee's knowledge is considered to evaluate the potential influence of the spatial change on the evacuation efficiency.

In General, other related work in emergency evacuation includes work by Filippopolitis et al. (2008) presented emergency simulation system using wireless sensor networks to monitor the spread of the hazards while an external event generator provides input to the sensors, while Filippopolitis and Gelenbe (2009) suggested a distributed decision support system designed for providing directions to evacuees during the evacuation of a building in the presence of a spreading hazard. In other work, Filippopolitis et al. (2009) evaluated network of decision nodes and sensor nodes on the one hand, and a wireless network for two-way communication between trapped civilians and an operation centre on the other hand. Research efforts have been put to compute the motion of an individual agent (Gelenbe and Cao, 1998) and to survey autonomous motion (Gelenbe et al., 1997).

Dimakis et al. (2010) who propose a distributed building evacuation simulator tool to support the evaluation of alternative emergency courses of action in confined environments such as buildings or ships. Gorbil and Gelenbe (2012) proposed the use of opportunistic communications to provide emergency evacuation support in built areas when other means of communication have broken down, and also investigates the resilience and performance for this communications. Moreover, Gelenbe and Wu (2013) discussed future research on emergency management systems that rely on sensor networks to locate hazards and people, both evacuees and emergency personnel, and communications between evacuees and emergency personnel. Other work Akinwande et al. (2015) investigated the use of dynamic grouping of evacuees based on their characteristics through using the concepts of the Cognitive Packet Networks (CPN) which uses a neural algorithm based technique for finding paths.

### 2.3. Ranking and Selection procedures

Ranking and Selection (R&S) procedures are developed to choose the best population or a subset that contains the best from competing alternatives (Goldman et al., 1991). These statistical procedures are classified into two general approaches: indifference-zone selection procedures (IZP) and subset selection procedures (SSP). The formal procedure (IZP) provides a guarantee of selecting the single best system, where an indifference-zone parameter  $\delta$  represents the range and the experimenter is "indifferent" to alternatives within  $\delta$  of the best system. Whereas, later procedure (SSP) chooses a subset of the available alternatives so that there is a defined probability guaranteeing that the subset includes the best system (Wang et al., 2011). Several studies on R&S procedures have been reported in the simulation field. Kelton and Law (2000) introduced R&S with references to more advanced concepts. Nelson et al. (2001) provided new perspectives that included a comprehensive state of the art review of R&S in simulation. The study represented a compromise between R&S procedures and fully

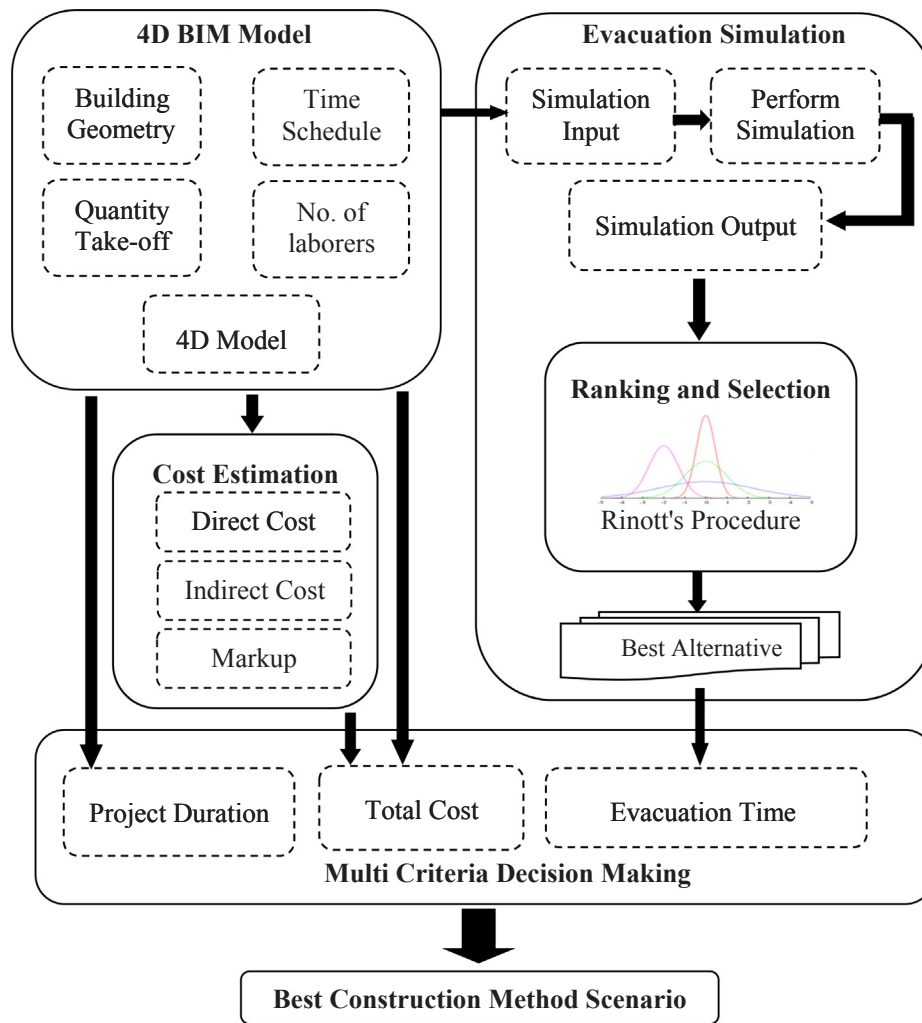


Fig. 1. Components of proposed framework.

**Table 1**  
Walking speeds on stairs in MassMotion (Oasys 2014).

Direction of travel	Angle X (degrees)	Percent of natural speed
Up	$0 < X < 27$	42.5
Up	$27 \leq X \leq 32$	Interpolated between 42.6 and 37.8
Up	$32 < X$	37.8
Down	$0 < X < 27$	57.4
Down	$27 \leq X \leq 32$	Interpolated between 57.4 and 49.8
Down	$32 < X$	49.8

sequential procedures that incorporates more restrictive assumptions. Goldsman et al. (2002) presented three R&S procedures for use in steady state simulation experiments. It provided an evaluation of simulation design and analysis of the three procedures, and illustrated the results based on this evaluation. Kim and Nelson (2006) provided texts regarding the overview of R&S. It described the challenges and opportunities faced in adapting ranking-and-selection techniques to stochastic simulation problems.

### 3. Proposed framework

The main objective of the framework is to advise the contractor regarding the simulated emergency evacuation test prior to construction, if the planned construction procedure is appropriate and should be adopted. To this end, the framework is designed and implemented to help decision makers in planning evacuation for construction sites and

**Table 2**  
Component social forces.

Force	Description
Goal	Force required to nudge agent so that it is at its desired speed heading towards its target
Neighbour	Repulsive force from each neighbour within range
Cohesion	Force pushing towards centroid of neighbours with similar targets
Collision	Force pushing agent away from collisions with oncoming neighbours
Drift	Force pushing agent in bias direction when faced with oncoming agents in narrow spaces
Orderly Queuing	Force pushing agents towards the middle of a target when approaching
Corner	Force pushing agents to hug a corner or swing wide

to select the appropriate construction procedure alternatives. The framework consists of five main components; 4D BIM Model, Cost Estimation, Evacuation Simulation Model, Ranking and Selection, and Multi Criteria Decision Making. Fig. 1 describes a schematic diagram for the proposed framework and its components. The following sections describe in more detail the seven components of the proposed framework.

#### 3.1. BIM model

Building Information Modeling (BIM) is used to build an adaptable

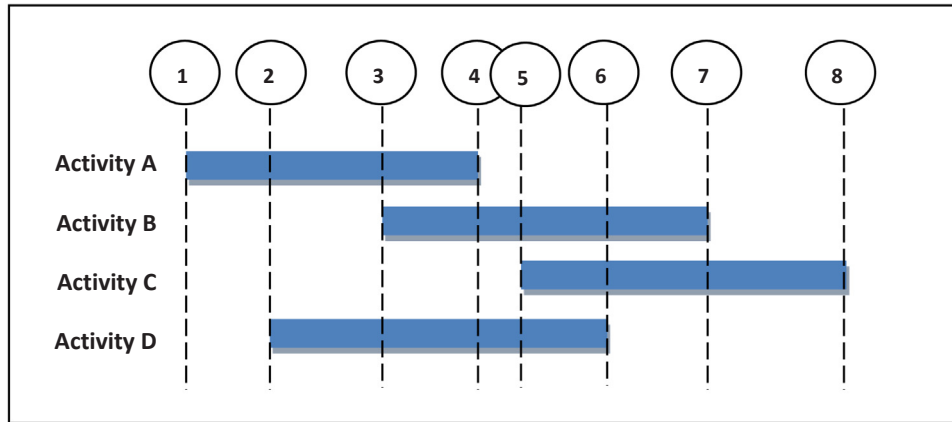
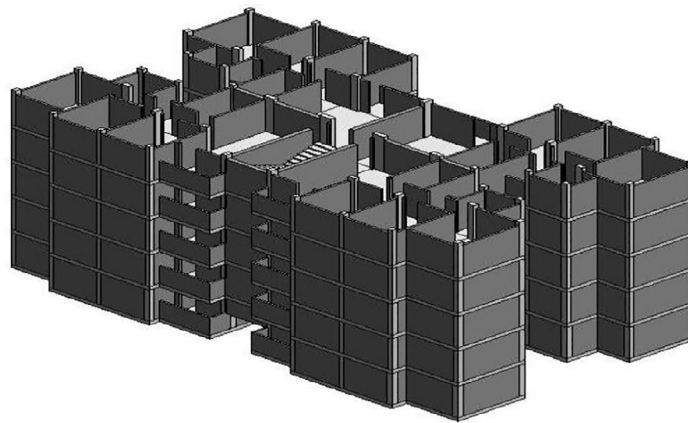


Fig. 2. Time points selected for each construction methods scenario.



a) 3D View



b) Building Zones and Rooms

Fig. 3. Egyptian social housing project.

3D virtual reality environment, which encompasses building geometry, geographic information, spatial relationships, properties and quantities of building elements. The proposed framework applies Autodesk Revit Structure software to establish the BIM model of a construction project. This BIM model provides geometric data (i.e., length, width, and height) of each building elements such as columns, walls, slabs, rooms, stairs, and opening doors. In addition, it defines the relationship between the each floor and its elements. Furthermore, BIM provides an Application Programming Interface (API) to facilitate data transfer to other different applications. The developers can add customized

toolbars, functionality, and connectivity to external application using programs written in C# language.

Microsoft Project is utilized for identifying the construction methods that are used in execution of a project. The activities and its resources that are required to complete the project are assigned in each construction method alternative and are identified. The total duration for each construction method can be calculated based on the quantity take-offs from the BIM and productivity rate for each activity crew. Moreover, the number of laborers per day is also determined.

4D modelling is an effective feature in the framework. It depends on

**Table 3**  
Required resource for finishing works activities.

	No	Activity description	Productivity	No of crews	No of labor for each crew	No of labor
Scenario 1	1	Block Works	100 m <sup>2</sup> /day	4	1 skill labor 2 labors	12
	2	Electrical Works	1 unit/day	2	1 skill labor 3 labors	8
	3	Plumping Works	2 units/day	2	1 skill labor 2 labors	6
	4	Plastering Works	120 m <sup>2</sup> /day	4	1 skill labor 3 labors	16
	5	Tiling Works	100 m <sup>2</sup> /day	4	1 skill labor 2 labors	12
	6	Painting Works	200 m <sup>2</sup> /day	4	2 skill labor 1 labor	12
	7	Doors & Windows Installation	20 unit/day	2	2 skill labor 2 labors	8
Scenario 2	1	Block Works	75 m <sup>2</sup> /day	3	1 skill labor 2 labors	9
	2	Electrical Works	1 unit/day	2	2 skill labor 2 labors	8
	3	Plumping Works	2 units/day	2	2 skill labor 1 labor	6
	4	Plastering Works	90 m <sup>2</sup> /day	3	1 skill labor 2 labors	9
	5	Tiling Works	100 m <sup>2</sup> /day	4	1 skill labor 2 labors	12
	6	Painting Works	200 m <sup>2</sup> /day	4	2 skill labor 1 labor	12
	7	Doors & Windows Installation	20 unit/day	2	2 skill labor 2 labors	8

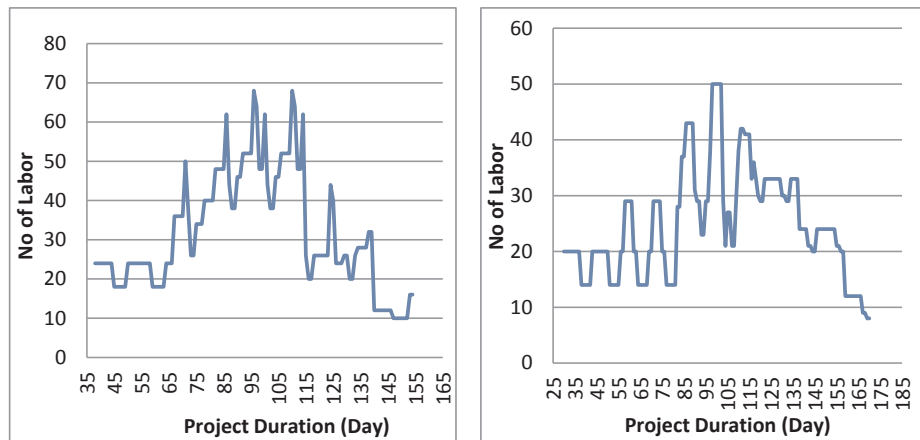


Fig. 4. Number of labors in Scenario 1 & 2.

linking elements of the 3D model with the activities of the construction schedule for visualization, thus, the user can visualize what is to be constructed on a specific date, the completed work on this date, and the feature also has an important role in determining the labor location for each activity. The add-in tool is developed in the Revit software to aid in creation of 4D models using the Application Programming Interface (API) through the C# environment. This add-in tool connected with Autodesk Revit using a text file contains developed code generated by C#. It is created in the specific folder where Revit Structure is installed. When users open BIM in Autodesk Revit Structure, the add-in tool will appear in a ribbon bar. By clicking the ribbon bar button, the Timeliner would initiate the Revit API and show the main plug-in form that includes various function buttons. This tool includes six different functions and each function can be called individually from the main C# module. It consists of the following tasks:

- *Browse file*: To enable users to select a Microsoft project file that is saved in CSV format to retrieve: the list of construction activities,

the relationship between activities, and start time and finish time for activities.

- *Assign Selected Elements*: To select and link the building elements with specific dates.
- *Add Selected Elements*: To add new elements for any specific date.
- *View Selected Elements*: To view the selected element of a building.
- *View Model*: To view the 3D model at any date for the time schedule.
- *Export IFC Model*: To export the 4D model at any date to the specific external folder.

In the proposed framework, the 4D modelling is used to link building elements from the 3D BIM model with a time schedule to produce the 4D model. The user imports project schedule data (CSV file format) which stores activities names, durations, early times (start and finish) from MS-Project by clicking the Browse button in the main form of the add-in tool. Once the file browses, the dates of the schedule project appears in the calendar with the related activities beside the calendar. Next, the user selects the element from the Revit visualization

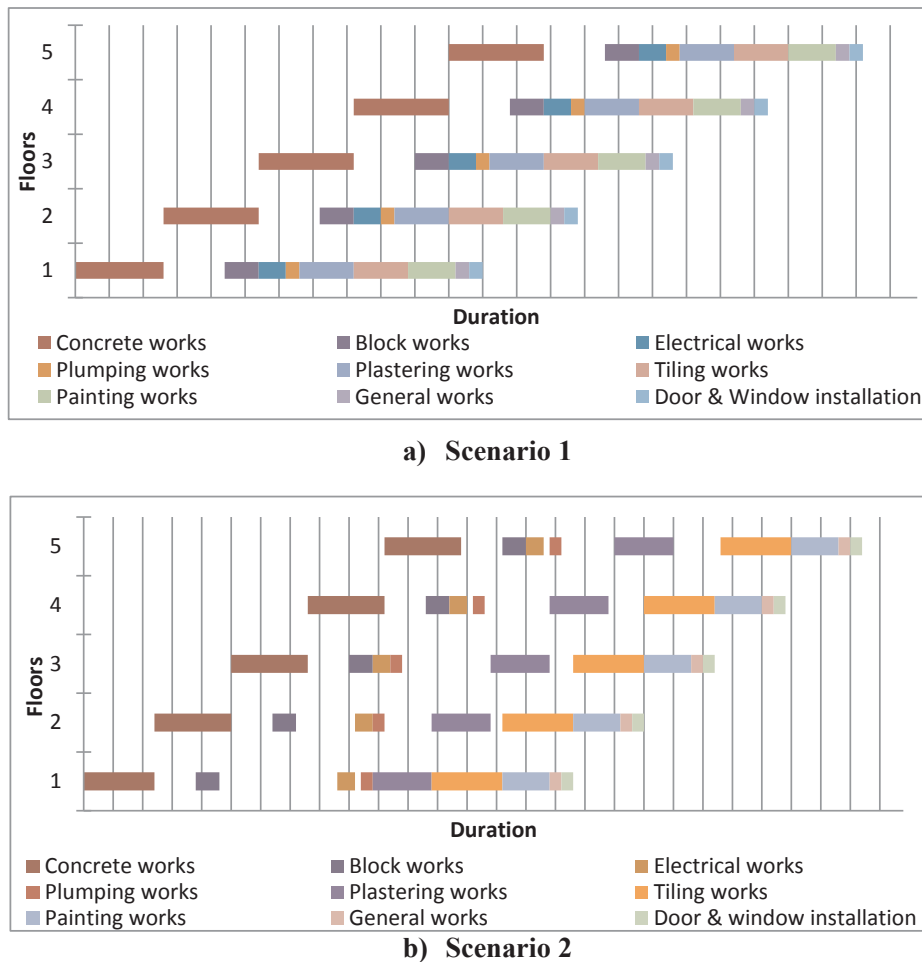


Fig. 5. Sequence of activities scheduled times.

**Table 4**  
Estimated direct cost (in LE) for the different construction methods.

No	Activities	Construction Method (Scenarios)			
		1	2	3	4
1	Excavation Works	8000	8000	9000	10,000
2	Foundation Works	243,534.8	238,110.6	254,839.4	269,040
3	Column Works	119,000	112,000	122,850	161,500
4	Slab Works	600,000	560,000	621,200	850,000
5	Stair Works	25,500	24,000	26,250	29,250
6	Block Works	191,340	181,533	204,885	236,295
7	Plastering Works	206,125	189,265	243,650	281,175
8	Tiling Works	152,000	142,925	160,1912.5	177,312
9	Painting Works	332,750	290,000	375,500	448,050
10	Electrical Works	100,000	100,000	110,000	117,500
11	Pumping Works	90,000	90,000	91,000	95,000
12	Aluminum Works	131,400	131,400	131,400	138,600
13	Door Works	154,000	154,000	154,000	165,900
Total Direct Cost		2,353,650	2,221,234	2,505,487	2,979,622

**Table 5**  
Estimated direct cost for the different construction methods.

Cost components	Construction Method (Scenarios)			
	1	2	3	4
Direct cost	2,353,650	2,221,234	2,505,487	2,979,622
Indirect cost related time	308,000	340,000	250,000	200,000
Indirect cost Independent time	176,523.7	166,592.5	187,911.5	223,471.7
Total direct & indirect	2,838,174	2,727,826	2,943,398	3,403,094
Markup (10%)	283,817.4	272,782.6	294,339.8	340,309.4
Total cost (LE)	3,121,991	3,237,738	3,000,609	3,743,403

elements is complete, the user exports all geometric building elements at any date of the schedule to Industry Foundation Classes (IFC) file format through Export IFC Model button and is stored in an external folder for simulation.

3.2. Cost estimation

The cost components for different construction method scenarios are direct cost, indirect cost, and markup margins. The direct cost estimation was done by exporting the quantity takeoffs from BIM to a Microsoft Excel sheet. The cost estimation calculations are performed by multiplying the activity unit prices by its quantity. The Indirect cost considers the cost components proposed by Marzouk and Moselhi (2002) and Assaf et al. (2001), and input received from experts in construction. The indirect cost components considered in the model

screen via mouse clicks. Once all the building elements related to activities associated with a specific day are highlighted, the specific day has to be selected 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 viewing the work tasks of the schedule along with the visual of the 3D model at any day through View Model button. The user can add new elements at any date of the linking process by selecting the element and pressing the added Selected Elements button. When the linking process for all

**Table 6**  
Number of labors and location at selected time points.

Time points	Activities	No of activities	Floor	No of labor	Total labors
1	Block Works	2	1	12	36
	Slab Works		2	24	
2	Tiling Works	4	1	12	44
	Electrical Works		2	8	
	Plumping Works		2	6	
	Columns Works		4	18	
3	General Works	5	2	8	68
	Doors & Windows Installation		2	8	
	Tiling Works	5	3	12	
	Block Works		4	12	
	Slab Works		5	24	
	Painting Works		1	12	

calculations are classified in two groups according to their relation with the execution of time. The first group is general and administrative expenses, and second group is field summary costs. These components are either time-related or time-independent. The total cost which is the sum of (direct and indirect costs) and markup for different construction method execution scenarios of the project is calculated. The markup percent includes profit and any contingency margins.

3.3. Evacuation model

Computer simulation is adopted using agent-based simulation to model the behavior of labor in evacuation situations. The proposed simulation model utilized MassMotion software provided by Oasys MassMotion Software (2014), as a simulation engine to implement agent-based simulation. The evacuation model is established taking into consideration continuous space, discrete time and modified social force. The simulation model is built based on the different construction methods scenarios. The input calibration of the model has been made in accordance with the description of the different scenarios. Building geometry was developed with MassMotion software to perform the evacuation analysis using the MassMotion interface. The users can import the IFC format file including building geometry, and convert reference geometry into a MassMotion object. The user creates the portals object serving as the entrance and exit points. These portals are used to generate labor at a specific location for each floor. The information about the modelling aspects which are used in the simulations of the agents and their behavior contains characteristics such as walking speeds, body dimensions of the agents, and behavioral modelling. In the model, the labor behaviors are modeled in such a way that it influences the evacuation process. However, the speed of the labor groups are varied in the model, based on the labor density. In order to present as realistic scenarios as possible, real data (if possible) is used in the calibration of the model.

Walking speed is an important element used in evacuation models. Every agent in MassMotion has a randomly assigned natural walking speed. 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 on different floors to the assembly point. Agent speed on the stairs could be divided into two situations: up-stair and down-stair, agent speeds down-stair are slightly quicker than those up-stair, but the difference is not so obvious. Generally, agent speeds on stairs are prescribed within MassMotion based on Fruin’s speed profiles (Fruin’s, 1971). Table 1 represents the walking speed on stairs in MassMotion depending on the slope of the stairs.

Agent size is included in the MassMotion calculations. Fruin (1971)

discusses a body ellipse of dimension 0.6 m by 0.4 m with an area of 0.2 m<sup>2</sup>. The value of the body radius used in the model is 0.25 m that is nearly identical while being far more efficient in computing agent movements and interactions. Moreover, this model is designed based on the assumption that the labor is familiar with the building and the construction site.

In MassMotion, the social force algorithm generates a series of forces based on the agent’s desired target, the presence of neighboring agents, and the location of obstacles. These forces are summed together and used to modify the agent’s acceleration as shown in Table 2.

The evacuation model takes into consideration both static and dynamic obstacles. The static obstacles can be walls, formwork, etc and the dynamic obstacles can be other agents that have their own speed, size, etc. Therefore, the agents are not allowed to collide with other agents, and occupant avoidance behavior which helps the occupant to move around the obstacles and walls. The labor agents are generated at the locations randomly for each activity according to different works for the project. Their locations are changed in each run round of the simulation. In the simulation, The initial orientation of each labor agent is randomly chosen from an angle of 0° to 360°. In order to avoid the bias caused by the initial direction of movement.

In evacuation modelling, there are many stochastic variables which are used to define the characteristics of the agents, such as walking speeds, and agent size. So, it is necessary to define the number of runs to be simulated to get converged result irrespective of the stochastic variables. The simulations in this research study are run in real-time, which means the time spent in the virtual environment equals the time in the real world. I.e. if a simulation of an emergency evacuation takes two minutes on the computer, it means that in the real world the evacuation is considered to take two minutes as well on the premise that simulation can represent reality.

Different construction method scenarios are implemented in the proposed framework. These scenarios take into consideration the sequences of the execution of construction activities during the project and the quantity of labor for each activity. The evacuation simulation is performed at different time points on the time schedule. These time points are chosen during project execution according to change in assigned resources associated with activities and activity location. To show the various emergencies connected with the progress of work, the time points are chosen at start times and finish times for activities as shown in Fig. 2.

The labor agents are generated at the locations randomly for each activity, according to different works for the project. Their locations change for each run cycle of the simulation.

3.4. Ranking and Selection procedure

Ranking and Selection (R&S) problems are those that compare a finite number of simulated alternatives and select the systems that qualify under pre-specified criteria (Bechhofer et al., 1995). After the evacuation results for the different construction method scenarios are presented, R&S statistical procedures are used to determine the best simulated model configuration among the considered four construction method scenarios. The Rinott’s procedures (Rinott, 1978) are implemented to rank and select the evacuation time for these scenarios. The Rinott’s procedure is performed in several steps as described below:

Step 1: Calculate the first stage sample means and variances:

$$\bar{X}_i^{(1)}(n_0) = \frac{\sum_{j=1}^{n_0} X_{ij}}{n_0} \tag{1}$$

$$\bar{S}_i^2(n_0) = \frac{\sum_{j=1}^{n_0} (X_{ij} - \bar{X}_i^{(1)}(n_0))^2}{n_0} \tag{2}$$

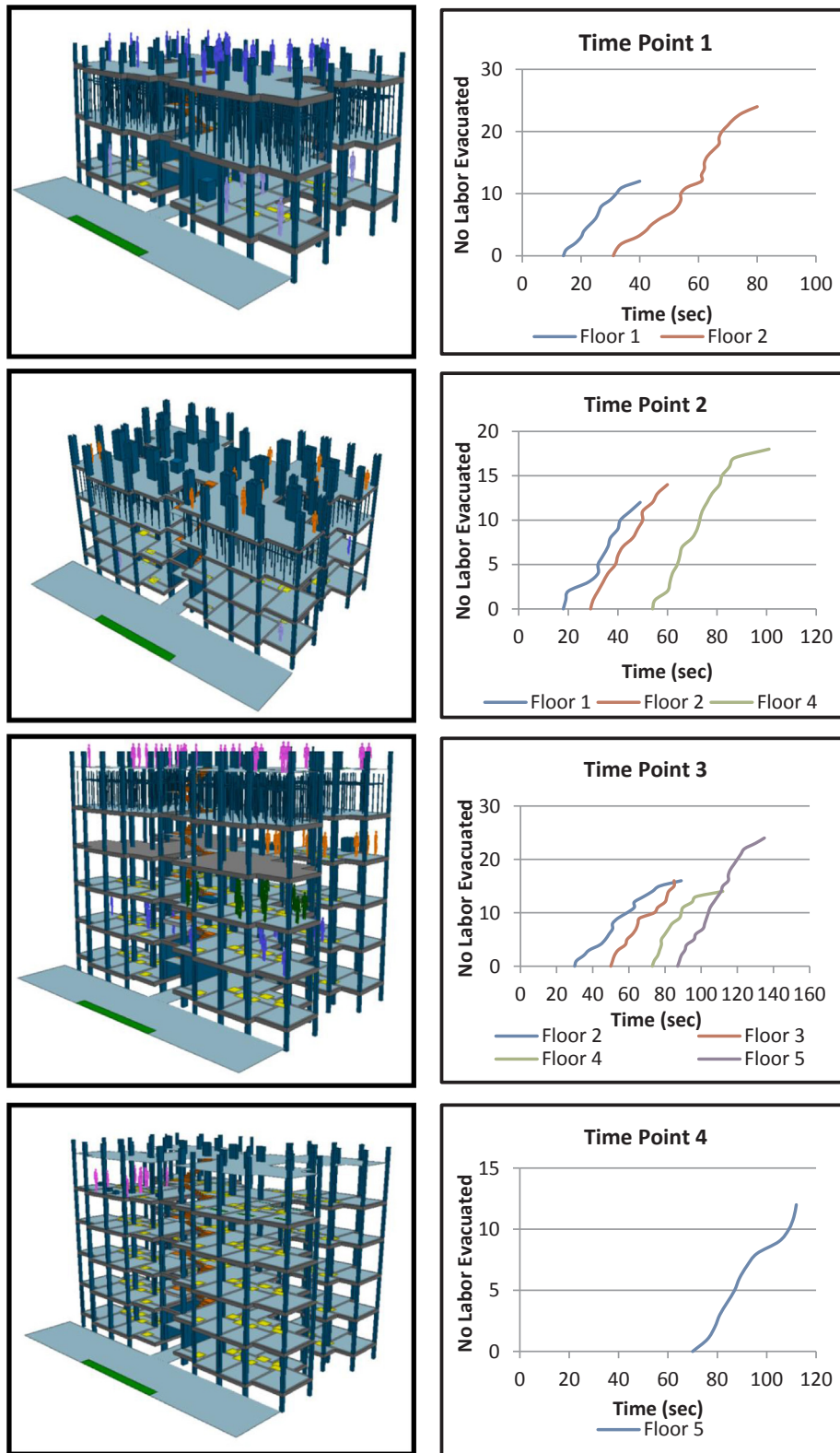


Fig. 6. Graphical representation at selected time points.

Step 2: Compute the final sample size needed for each alternative i:

$$N_i = \max \left\{ n_0, \frac{h_1^2 S_1^2}{\delta^2} \right\} \quad (3)$$

Step 3: Make  $(N_i - n_0)$  additional replications of each alternative 'i',

compute the second-stage means  $\bar{X}_i^{(2)}(N_i - n_0)$

$$\bar{X}_i^{(2)}(N_i - n_0) = \frac{\sum_{j=n_0+1}^{N_i} X_{ij}}{N_i - n_0} \quad (4)$$

Step 4: Define the weights:



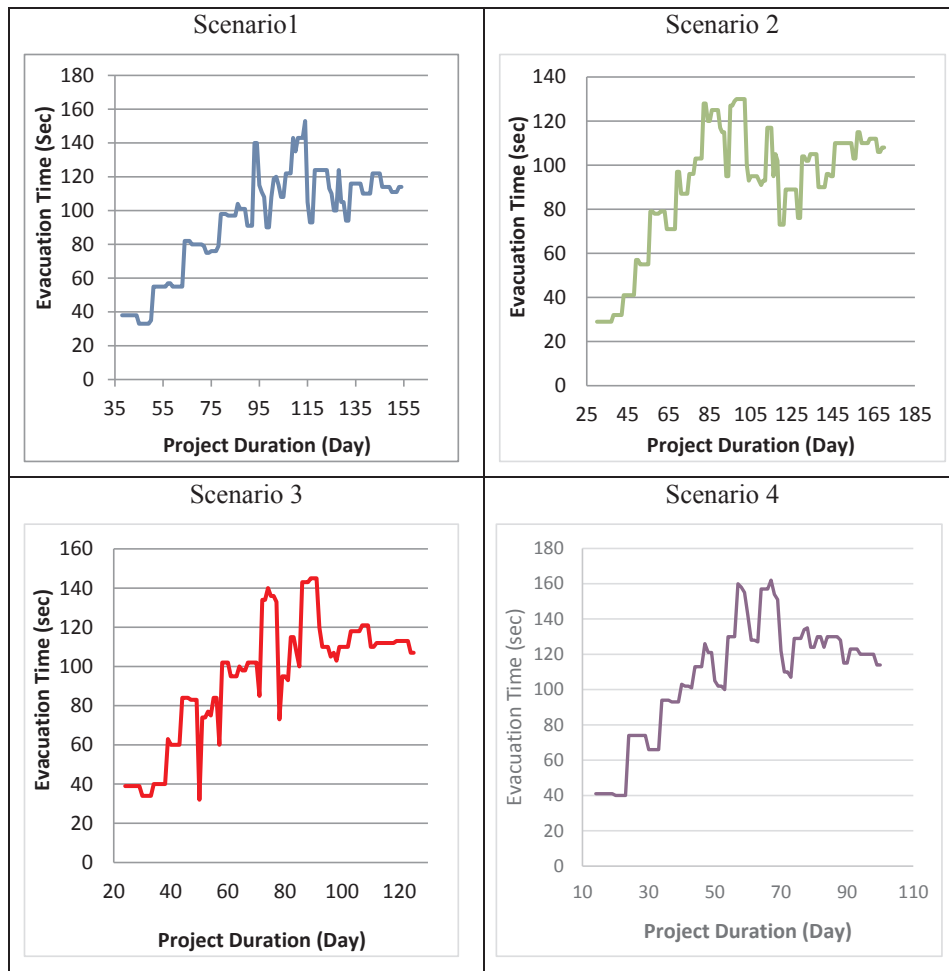


Fig. 7. Simulation results for the different scenarios.

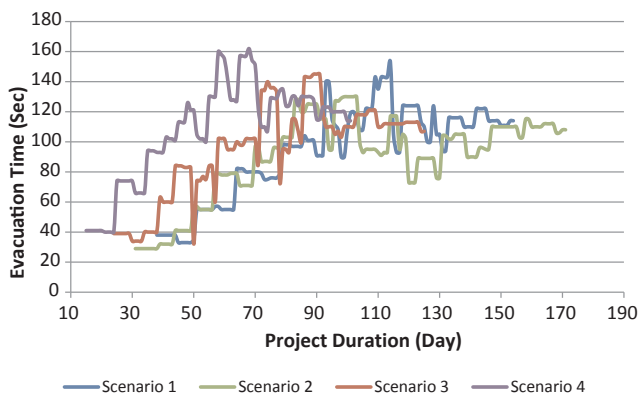


Fig. 8. Comparison of simulation results of different scenarios.

$$W_{i1} = \frac{n_0}{N_i} \left[ 1 + \sqrt{1 - \frac{N_i}{n_0} \left( 1 - \frac{(N_i - n_0)\delta^2}{h_i^2 \delta_i^2(n_0)} \right)} \right] \quad (5)$$

$$W_{i2} = 1 - W_{i1}, \text{ for } i = 1, 2, \dots, k \quad (6)$$

Step 5: Define the weighted Sample Means and select the alternative with the smallest weighted mean

$$\bar{X}_i(N_i) = W_{i1} \bar{X}_i^{(1)}(n_0) + W_{i2} \bar{X}_i^{(2)}(N_i - n_0) \quad (7)$$

Step 6: Select the alternative with the maximum weighted mean

### 3.5. Multi Criteria Decision Making (MCDM)

Multi Criteria Decision Making (MCDM) is applied to help in selecting the suitable construction method scenario. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is used to identify the best construction method scenario taking into consideration three main criteria which are: construction total cost, execution time, and evacuation time of the labor (safety considerations). TOPSIS process contains six steps as listed below:

Step 1: Normalize the decision matrix

$$r_{ij} = x_{ij} / \sqrt{\sum_{i=1}^m x_{ij}^2} \quad i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n. \quad (8)$$

Step 2: Construct the weighted normalized decision matrix by multiplying the normalized decision matrix by its associated weights as:

$$v_{ij} = r_{ij} \times w_j \quad i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n. \quad (9)$$

Step 3: Determine the positive and negative ideal solution.

$$A^* = \{(\max_i v_{ij} | j \in C_b), (\min_i v_{ij} | j \in C_c)\} = \{v_j^* | j = 1, 2, \dots, m\} \quad (10)$$

$$A^- = \{(\min_i v_{ij} | j \in C_b), (\max_i v_{ij} | j \in C_c)\} = \{v_j^- | j = 1, 2, \dots, m\} \quad (11)$$

Step 4: Calculate the separation measure from the positive and

negative ideal solution

$$S_i^* = \sqrt{\sum_{j=1}^m (v_{ij} - v_j^*)^2} \quad \text{where } j = 1, 2, \dots, m \quad (12)$$

$$S_i^- = \sqrt{\sum_{j=1}^m (v_{ij} - v_j^-)^2} \quad \text{where } j = 1, 2, \dots, m \quad (13)$$

Step 5: Calculate the relative closeness to the ideal solution.

$$RC_i^* = \frac{S_i^-}{S_i^* + S_i^-} \quad \text{where } i = 1, 2, \dots, m \quad (14)$$

Step 6: Rank the preference order

#### 4. Case study

This section describes the implementation of the proposed framework for the construction of a building in an Egyptian social housing project. Housing projects are important projects that serve the low-income population in Egypt. The main characteristics of these projects that are considered in this study are: repetitive and typical units, the number of floors is five floors since this type of building is not equipped with elevators, height of floor-to-floor is 3 m, and the width of the stair in the building is 1.0 m. The 3D Model is developed in BIM using Autodesk Revit Structure software (see Fig. 3). All the floors have the same layout and the area of each floor is divided into four zones to facilitate the determination of labor locations and each zone consists of rooms that are numbered with a unique number for use in the simulation software as shown in Fig. 3.

The construction duration is divided into two main stages that represent major changes in space: The first stage starts with excavation works and finishes by the completion of the ground floor skeleton work. This stage is not considered in evacuation calculation. The second stage starts with the first floor skeleton works and finishes with the completion of the fifth floor.

The quantities of different materials in BIM is specified and extracted to an external Excel spread sheet. Based on the quantity takeoff from Revit and productivity rate for each activity crew, the project schedule and the quantity of labor in each day during the execution of the project are determined. Table 3 lists productivity rate and required resources for a number of activities for scenarios 1 & 2.

Four construction method scenarios are implemented in the proposed framework taking into consideration the sequence of activities, the quantity of labor for each activity, and the duration of activities. The project execution duration is estimated for each construction method scenario. For example, the total duration of the construction project in construction method Scenarios 1 & 2 is 154, 170 days respectively. Figs. 4 and 5 represent examples of the quantity of labor for each day during execution of the project and the sequence of activities based on the activity early times for construction methods in scenarios 1 & 2.

The cost components for different construction method scenarios are direct cost, indirect cost, and markup margins. The direct cost estimation was done by exporting the quantity takeoffs from BIM to a Microsoft Excel spread sheet. Multiplying the unit prices for each activity and its quantity produces the cost estimation for the activity. Table 4 lists the activities and direct cost for each construction method (four scenarios). For the considered case, Field General and Administrative and Field Summary Cost are considered 50,000 L.E/month and 7.5% of Direct Costs, respectively. Table 5 lists the detailed components of total cost for the different construction methods.

The 4D model is created using the 3D model from BIM and construction project scheduling to determine the various points in time during project execution. According to these selected points, the

simulation model is used to estimate the labor evacuation time for each floor and stairway until the assembly point location outside of the construction site is reached. A series of evacuation simulations have been conducted in different scenarios using MassMotion software. These scenarios explored the influence of different construction methods during execution of the project on the labor evacuation time. The evacuation processes began with the first slab works for all of the construction method scenarios. For example, four time points were chosen to illustrate estimation evacuation time for these points in construction method Scenario 1. Table 6 lists the information about activity execution in these points, the number of activities for each time point, the total quantity of labor for each activity, quantity of labor in each time point, and activity location. The evacuation model generates labor agents with random distribution at the defined locations.

Evacuation time is the most commonly used measure of effectiveness for evacuation planning. Furthermore, the evacuation process for each time point can be described by evacuation curves, which represent the cumulative number of laborers evacuated from the evacuation area as a function of time. Fig. 6 depicts the graphical representation of the time taken to evacuate labor inside the building at selected four time points and screen images of labor location using MassMotion modelling.

There are many time points that are simulated in the developed simulation model for each construction method (scenario) during execution of the project. The cumulative evacuation time is determined for selected points in time for each scenario and then portrays different evacuation times for all time points in a single graph. Fig. 7 represents the evacuation time of labor from the building construction site at different times that are selected for different scenarios during the project duration.

Based on the simulation results, the evacuation model is a profile of estimated evacuation times for the dynamically changing environment over the duration of the construction project. The results obtained from the simulation model reveal the evacuation time increase corresponding to the location of activities at successive floors. In addition, the labor evacuation from upper floors have a great influence on overall evacuation time for each time point since it increases evacuation time. Moreover, the results demonstrate that the stairway area is an important factor in the evacuation process, so more attention should be paid to safety aspects when preparing the emergency plan and that it should be free from any obstacles that would cause evacuations delays. The results indicate that the labor that worked in zones no. 3 and 4 near the stairs during slab work, reach the assembly point in less time than the evacuation time of the labor that worked in zones no. 1 and 2. Fig. 8 illustrates the comparison of evacuation times for the different construction methods (scenarios). The simulation results indicate small evacuation time is required at the beginning of project execution because of the limited number of activities, laborers and floors. On the other hand, the evacuation time increases with the expansion of the number of activities and labor density half-way through the project execution. It can be observed that Scenario 4 is higher than the rest of the scenarios because the duration of project execution in this scenario is small and the quantity of labor in each time point is large. The quantity of labor has a significant effect on the evacuation time. Increasing the quantity of labor will increase the time taken to evacuate from the building. The maximum evacuation time is 162 s in Scenario 4, slightly higher than 153 s of required evacuation time of Scenario 1.

According to the simulation results for the previous different scenarios, it should be noted that the concrete activities have a great influence on the evacuation time followed by the plastering activities and tiling activities. This is attributed to large quantity of labor associated with these activities which restricts the labor movement during the evacuation process. In addition, the evacuation of labor from upper floors has a strong influence on the overall evacuation time at each point in time, as the evacuation time increases.

After performing simulation analysis, R&S procedures (Rinott's Procedure) are implemented to compare selected points in time for each

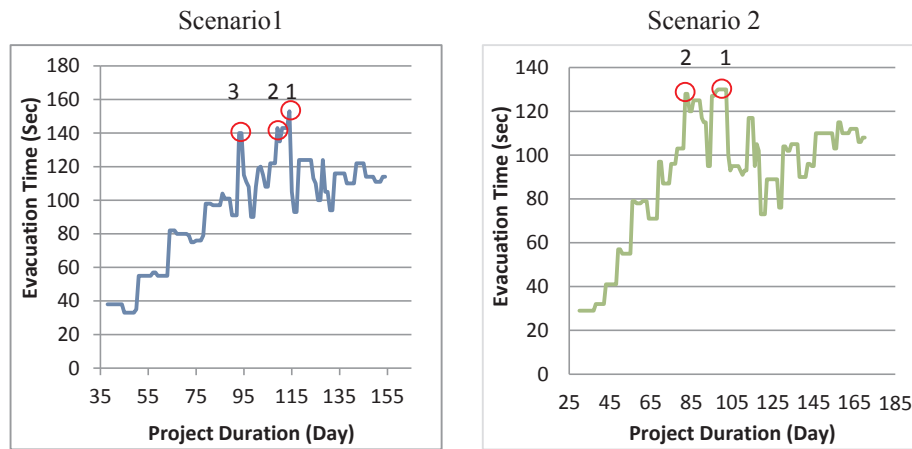


Fig. 9. The selected points in time for Scenario’s 1 and 2.

**Table 7**  
R&S results for the four scenarios.

Scenario	i	$\bar{X}_i^{(1)} (n_0)$	$S_i^2 (n_0)$	$N_i$	$\bar{X}_i^{(2)} (N_i - n_0)$	$W_{i1}$	$W_{i2}$	$\bar{X}_i (N_i)$
1	1	152.3	4.233	43	151.03	0.283	0.717	151.389
	2	142.7	3.34	34	141.58	0.35	0.65	141.974
	3	140.5	11.16	112	141.529	0.099	0.901	141.427
2	1	128	4.889	34	128.125	0.354	0.646	128.081
	2	130.8	6.62	46	130.028	0.269	0.731	130.236
3	1	142.6	9.6	66	142.393	0.178	0.822	142.42
	2	144.5	8.5	59	144.184	0.216	0.784	144.251
4	1	161.9	5.65	39	161.414	0.297	0.703	161.558
	2	160	4.88	23	161.231	0.465	0.535	160.659

**Table 8**  
Alternatives for construction method scenarios.

Scenario	Total cost (L.E)	Duration (Days)	Evacuation Time (S)
1	3,121,991	154	151.4
2	3,157,191	170	130.2
3	3,045,626	125	144.3
4	3,003,191	100	161.8

**Table 9**  
Distributive normalization and weighted normalized decision matrix.

	Scenario	Total Cost (L.E)	Duration (Days)	Evacuation Time (S)
Distributive Normalization	1	0.47	0.55	0.51
	2	0.49	0.61	0.44
	3	0.46	0.45	0.49
	4	0.57	0.36	0.55
Weighted Normalized	1	0.052	0.171	0.298
	2	0.054	0.188	0.256
	3	0.050	0.139	0.284
	4	0.063	0.111	0.318

scenario and to find the best point that maximizes the expected evacuation time for each construction method scenario. For a set of normal random variables  $X_{ij}$  with different means  $\mu$  and variances  $\sigma^2$  to represent the competitive points  $X_{ij} \sim N(X_i, \sigma_i^2)$ , it is required select a design with the maximum mean.

For Scenario 1, the input parameters are:  $k = 3$ ,  $\alpha = 0.05$ , the indifference amount  $\delta$  is set to one second, and initial replications

$n_0 = 10$ , so the Rinott's constant  $h$  (from the tables in Wilcox, 1984) is 3.165. In Scenarios 2, 3 and 4, the number of total of selected point in the scenarios are two ( $k = 2$ ). Rinott's constant  $h = 2.615$  for confidence level 95%. Fig. 9 illustrates an example for the selected points in Scenario 1 and 2.

The calculation results for an evacuation time for the different scenarios are listed in Table 7. The results indicate that the first time point is the best evacuation time with the largest mean value in Scenario 1. The R&S results for evacuation time in Scenario 2 shows that the second case has the largest evacuation time value. As a result, we choose the second case as the best evacuation time. Similarly, the results for Scenario 3 and 4 shows the first and second cases are the best but also contain the highest evacuation time.

Multi Criteria Decision Making is applied to select the best construction method scenario using the TOBSIS method. Table 8 lists four different alternatives resulting from the different construction method scenarios. The table shows a matrix describing each alternative in terms of various construction execution method values of the project. The TOPSIS method is used to select the best construction method alternative. TOPSIS then ranks these alternatives, taking into consideration three criteria which are project total cost, expected project duration and evacuation time associated with each construction method alternative.

Analytic Hierarchy Process (AHP) technique is used to assign the weights to three different criteria. Relational data is derived from questionnaires administered on five construction sites to determine the order of importance of the construction method scenario criteria. The pairwise comparison process elicits qualitative judgments that indicate the strength of the experts' preference in a specific comparison according to Saaty's 1–9 scale. Final weights are calculated by taking the arithmetic average of the weights obtained from pairwise comparisons of experts. Evacuation time has the most weight (58%), followed by the duration (31%), and finally, the total cost (11%). The distributive normalization method and weighted normalized decision matrix are listed in Table 9. The positive and negative ideal values are then identified. It is worth noting that the objective is to minimize project total cost, project duration, and evacuation. Accordingly, the best and worst values for each criteria are identified and tabulated as per Table 10.

After identification of ideal values, the “virtual” Euclidean distances for each alternative to the best ideal and to the worst ideal are both calculated as shown in Tables 11 and 12. Following the calculations, a relative closeness coefficient is computed for each alternative. Table 13 lists the closeness coefficient calculation for the four construction method alternatives evaluated. Using TOPSIS, the best construction method scenario is Scenario 3. This construction method has a total cost of 3,000,609 L.E, total duration of selected construction method is 125 days and the evacuation time is 144.3 s.

**Table 10**  
Determination of ideal values.

Ideal solution	Total Cost (L.E)	Duration (Days)	Evacuation Time (S)
Positive ideal solution $A_j^+$	0.05	0.11	0.26
Negative ideal solution $A_j^-$	0.06	0.19	0.32

**Table 11**  
Distance to best ideal value.

Scenario	Total Cost (E.L)	Duration (Days)	Evacuation time (S)	$d_i^+$
1	0.000004	0.003582	0.001734	0.072939
2	0.000016	0.006018	0.000000	0.07768
3	0.000000	0.000768	0.000761	0.039103
4	0.000154	0.000000	0.003803	0.062906

**Table 12**  
Distance to worst ideal value.

Scenario	Total Cost (E.L)	Duration (Days)	Evacuation Time (S)	$d_i^-$
1	0.000108	0.000314	0.000401	0.028693
2	0.000072	0.000000	0.003803	0.062244
3	0.000154	0.002487	0.001161	0.061665
4	0.000000	0.006018	0.000000	0.077579

**Table 13**  
Closeness coefficient calculation.

Scenario 1	0.28
Scenario 2	0.44
Scenario 3	0.61
Scenario 4	0.55

**5. Conclusions**

This paper presented a framework for the planning of emergency evacuation of labor for construction sites during project execution. It provides a platform that integrates Building Information Modelling (BIM) and computer simulation, taking into account different construction method for project execution. The proposed framework utilizes Building Information Modelling (BIM) and MS Project for developing 3D models and project schedule to produce 4D models. In conjunction with this, an evacuation model was developed to provide contractors with the time needed to emergency evacuate labor at construction sites during project execution.

This evacuation model is used to calculate the total evacuation time on each floor and the stairs until the assembly point outside the location and investigating the possibility for construction workers to safely evacuate over the duration of the project by drawing a profile of evacuation time that changing based on change of project activities over the duration of construction project. In addition, the simulation analysis highlights potential areas of localized congestion through a visual representation of labor movements during the evacuation process and to demonstrate the significant influence of the activities sequencing on evacuation times in construction sites. Rinott’s procedures were carried out in this paper to determine the anticipated evacuation time for different scenarios as well as TOPSIS multi criteria decision making method to choose the best construction method. This study method can be expanded in the future to account for evacuation simulation for outdoor processes as well as developing a methodology that is capable of adjusting the plans, with feedback during the ongoing evacuation process.

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