ORIGINAL PAPER

Construction site layout optimization model considering cost and safety in a dynamic environment

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Abstract

The construction industry is a complex field that requires lots of planning to succeed. The first step of planning in a construction project is planning the construction site layout. This paper develops a model formulation to optimize the construction site layout from the perspective of cost and risk. The developed optimization model also takes into consideration the dynamic environment of a construction site. That is, it demonstrates the situation that occurs in reality, since facilities, locations and their dimensions may vary throughout construction stages. The model aims to minimize both the cost and the risk involved in the project in a dynamic environment. Both cost and risk are minimized for material flow, equipment flow, people follow, facility setup, facility dismantling and facility relocation. The model generated in this paper was solved by standard branch-and-bound technique using LINGO software. To verify the model, a case study was solved using the generated model and results were compared to the same project completed in reality.

Keywords Optimization · Dynamic construction site layout · Cost · Risk · Material flow · Equipment flow · People follow · Facility setup · Facility dismantling and facility relocation

General introduction

The process of construction is very complex and involves numerous aspects that have to be studied and planned for. The first and most important step in construction projects' success is careful planning. Planning a construction project is considered to be the basis of its success (Ning et al. 2018). Project planning is extremely valuable since decisions and changes made at early stages of the project have a tendency to be more efficient than those made at later stages (Ning et al. 2018). When looking at a construction plan, one of the most important things to consider is the construction site layout. Developing the construction site layout is a vital action to make the most of the available site space. In addition, a good site layout plan contributes to minimizing the travel distances between facilities and thus, reducing related risks and costs (Said and El-Rayes 2013). Therefore, decisions such as proper allocation of construction site facilities should be studied intensely to choose the most suitable scenario of facility allocation. Such studies will improve construction site safety management, minimize related risks and costs and save time in both the preconstruction and construction stages (Ning et al. 2018).

Paper objectives, milestones and brief methodology

This paper has several objectives, which will be completed throughout its sections. This paper encompasses: introduction, literature review, methodology, analysis and results, discussion and conclusion. The paper aims to target the following milestones:

- Introduce the topic
- Illustrate the topic's importance

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- Highlight previous research done and their results
- Find gaps in the previously held research
- Build the framework of the paper
- Determine what the paper is going to measure and how to test it
- Study the previously generated models and generate a new one that optimizes the dynamic construction site layout taking into account related cost and risks
- Analyse the model using a case study
- Case Study is to be tested using a suitable software (LINGO)
- The real-life scenario of the case study is to be compared with the results generated by the model
- Discussion of results is to be held
- Form a conclusion about the work done

The methodology of this paper in brief comprises: the study of previous optimization models of construction site layout, study cost and risks that are related to allocation of facilities in a construction site, categorize them, come up with related assumptions, identify related variables, set constraints and implement all of these in an optimization model that minimizes costs and risks in the dynamic environment of a construction site.

Problem statement

The problem statement, which this paper addresses, focuses on merging six important variables that govern construction site. The proposed model considers dynamic environment in parallel to safety and cost. Those three attributes are linked to set of logistical variables as shown in Fig. 1.

Risks in a construction site layout

In the paper "Empirical Measurement and Improvement of Hazard Recognition Skill", the authors tested three different interventions for improving hazard recognition in a construction site. The data collection method is qualitative; data were collected from over 3000 h of field observations with 103 workers (Albert et al. 2017). Data were analysed using SAVES, SMQM and Hit techniques. The performance of hazard recognition was measured prior to each intervention and after the intervention is done with in depth analysis to come up with the conclusion that measures such as gravity, motion, mechanical and electrical hazards are linked with the peak baseline hazard recognition levels, while measures such as temperature, chemical, radiation and biological hazards were the least recognized hazards (Albert et al. 2017). This shows that there is a necessity for hazard recognition programs in a construction site (Albert et al. 2017). Hazard recognition is a critical step in enabling construction engineers to deal with risks imposed on site.
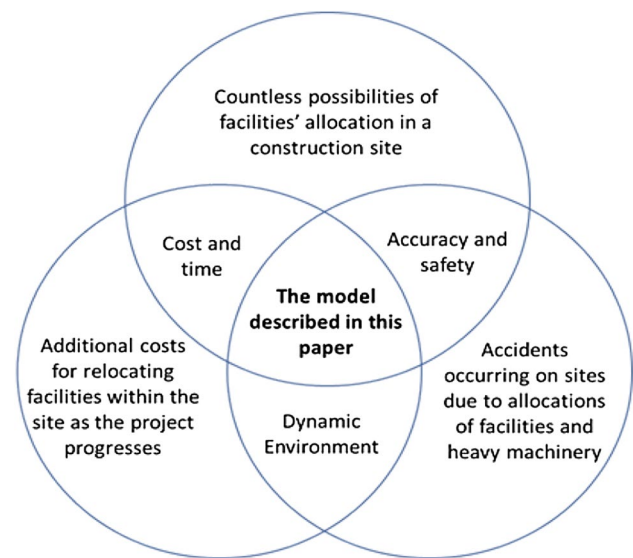

Fig. 1 Venn diagram simplifying problem statement

In addition, in the paper "Construction Safety Risk Drivers: A BIM Approach", the authors define five groups of safety risk drivers that can affect the probability or the consequences of an accident in a construction site layout (Malekitabar et al. 2016). The authors found out that designing for risk can contribute highly to risk avoidance (Malekitabar et al. 2016).

Construction site layout optimization

Optimization of cost in a static environment In the paper "Optimization of Tower Crane and Material Supply Locations in a High-rise Building Site by Mixed-integer Linear Programming", as the title indicates, the authors use mixed-integer linear programming, MILP, to optimize tower crane location in a construction site of a high-rise building (Tam et al. 2011). To simulate material transportation, quadratic assignment problem, QAP, is used, which was then linearized into mixed-integer linear problem that can be solved by standard branch-and-bound technique(Tam et al. 2011). The objective function of this model aims at optimizing costs involved in a static environment (Tam et al. 2011). Numerical examples were solved using the model generated and results were compared to those from genetic algorithm; the results show that MILP generates almost 7% improved objective function values (Tam et al. 2011).

Optimization of cost in a dynamic environment In the paper "Performance of Global Optimization Models for Dynamic Site Planning of Construction Projects", the authors carry out a comparison between two of the most widely used optimization models for dynamic construction site layout;

genetic algorithm (GA) and approximate dynamic programming (ADP) (Said and El-Rayes 2013). The comparison is held in terms of reaching the optimal solution (minimizing travel costs and relocation costs) and minimizing the computational time (Said and El-Rayes 2013). The authors perform this study through varying size and complexity of designed set of construction site layout problems (Said and El-Rayes 2013). The results of the comparison show that ADP outperformed GA in both; finding the optimal solution and minimizing the computational time (Said and El-Rayes 2013). On the other hand, GA proves to be a very practical tool because of its simplicity and multi-objective optimization capabilities (Said and El-Rayes 2013).

In the paper "Dynamic Construction Site Layout Using Ant Colony Optimization", as the name indicates, the author uses the ant colony optimization algorithm to optimize a dynamic construction site layout (Abdelrazig 2015). The following steps were applied to generate the ant colony optimization model in this paper: generate initial solution for each ant, use pair-wise exchange heuristic, pheromone trail matrix initialization, start main loop, perform R pheromone trail swaps, use the pair-wise exchange heuristic to improve the solutions, perform intensification strategy, update pheromone trail matrix and perform diversification strategy (Abdelrazig 2015). The model takes into account cost of fixing facilities and cost of shifting facilities; the objective function aim is to minimize costs (Abdelrazig 2015). The author then uses a case study of a highway to demonstrate the generated ant colony optimization model (Abdelrazig 2015). The studies in this paper found that ant colony optimization technique is found very efficient in solving dynamic construction site optimization problems (Abdelrazig 2015).

In the paper "Dynamic Site Layout Planning Using Approximate Dynamic Programming", the authors developed an approximate dynamic programming model that looks for and identifies global optimal dynamic site layout plans (El-Rayes and Said 2009). This model is very useful since it approximates how much future decisions in later stages of a project are affected by layout decisions made in early stages (El-Rayes and Said 2009). The authors developed the model on three stages: first is, "formulating the decision variables, geometric constraints, and objective function of the dynamic site layout planning problem", second is "modelling the problem using approximate dynamic programming" and third is "implementing and evaluating the performance of the model" (El-Rayes and Said 2009). The objective function of the model is aimed at minimizing three types of cost; travel cost, relocation cost and constraint violation cost (El-Rayes and Said 2009). Finally, a case study was used to test the generated model and demonstrate its capabilities (El-Rayes and Said 2009). Despite having some downfalls such as representations of facilities as

two-dimensional rectangles and taking the "resource travel paths as the shortest direct distance between site facilities", the model was proven to be very effective in approximate optimization of dynamic construction site layouts (El-Rayes and Said 2009).

The authors of the paper "Genetic Algorithm Optimization for Dynamic Construction Site Layout Planning" use genetic algorithm to generate an optimization model for construction site layout (Farmakis and Chassiakos 2018). This model takes into consideration several types of costs: "construction and relocation costs of facilities and transportation costs of resources moving from one facility to another or to workplaces" (Farmakis and Chassiakos 2018). The model also minorly takes into account the safety and environmental considerations related to facilities' operations and interconnections in the form of preferences or constraints measured by the proximity or remoteness of one facility to the other (Farmakis and Chassiakos 2018). The analysis was done dynamically; for several project stages, and case studies were applied through the Palisade's Evolver software to test and evaluate the model (Farmakis and Chassiakos 2018). The analysis outcomes indicated that the model has a reasonable response to inputs varying with time in relation to quality of output and time taken to generate results (Farmakis and Chassiakos 2018).

Optimization of transportation time The paper "GA Optimization Model for Solving Tower Crane Location Problem in Construction Sites" revolves around optimizing the location of tower cranes in a construction site (Abdelmegid et al. 2015). The objective function of this optimization model is to minimalize the total transportation time (Abdelmegid et al. 2015). The genetic algorithm approach was used to generate the mode and a numerical example was used to test and validate the model results (Abdelmegid et al. 2015). This model was proven very efficient in choosing the location most suitable for a tower crane in terms of: "shape and size of the buildings, type and quantity of required materials, crane configurations, crane type, crane height, boom length and capacity" (Abdelmegid et al. 2015). However, the model neither took into considerations related costs nor safety measures.

Optimization of safety and cost in a static environment In the paper "Trade-off between Safety and Cost in Planning Construction Site Layouts", the authors developed a model that is capable of minimizing travel costs and maximizing safety in construction site layout planning (El-Rayes and Khalafallah 2005). The authors use concepts and performance criteria that allow the quantification of safety and travel costs of resources in a construction area (El-Rayes and Khalafallah 2005). The safety in this model is demonstrated in three measures; safety of crane operation, control of haz-

ardous materials and travel routes intersections (El-Rayes and Khalafallah 2005). The authors implement the model in the form of a multi-objective genetic algorithm then an application example is used to illustrate the efficiency of the model in creating the optimum trade-off between travel cost and safety involved in a construction site layout (El-Rayes and Khalafallah 2005). This optimization model is, however, considering the construction site as a static environment; time was not a factor in this model, which is a drawback to its efficiency in the modern construction industry.

In addition, in the paper "Cost–safety Trade-off in Unequal-area Construction Site Layout Planning", a multi-objective optimization model that deploys modified Pareto-based ant colony optimization algorithm is used to optimize the handling cost between facilities and safety (minimize the number of accidents) in a construction site layout (Lam and Ning 2013). In this paper, the authors take into account the facility size and the available locations' sizes in order to get a more optimized solution (Lam and Ning 2013) unlike those of "Trade-off between Safety and Cost in Planning Construction Site Layouts". A case study was used to verify the model and the results were very satisfactory (Lam and Ning 2013). However, the findings of this paper are only for static situations of a construction site layout; construction stages are not taken into considerations.

Optimization of safety in a dynamic environment Furthermore, in the paper "Optimal Construction Site Layout Based on Risk Spatial Variability", the authors develop a model to optimize a construction site layout taking special risk variability into account (Abune'meh et al. 2016). This model consists of three major parts: modelling the construction site facilities under study, modelling hazard interaction matrix, which shows the hazard interaction between site facilities and how it changes with distance, modelling vulnerability interaction matrix, which shows how vulnerable each facility is to the hazards generated by the rest of facilities, developing utility function, which optimizes the construction site layout with the minimum risk and finally use spatial analysis to comprehend space configurations in the construction site layout and geographic information system (GIS) for its visualization (Abune'meh et al. 2016). Case studies were used to verify the model and the results proved its efficiency in optimization of a construction site layout with minimizing risks (Abune'meh et al. 2016). This paper is completely focused on optimization of construction site layout from a risk point of view and ignores related costs and time impacts.

Optimization of safety and cost in a dynamic environment Another paper that studies safety in a construction site layout optimization problem is "Optimisation of Site Layout Planning for Multiple Construction Stages with Safety Considerations and Requirements". The authors of this paper

develop a binary mixed-integer linear program to allow for optimization of construction site facilities within multiple construction stages (Huang and Wong 2015). The highlight of this model is its simplicity since it can be "solved by a standard branch-and-bound algorithm using the commercial software package LINGO" (Huang and Wong 2015). The aim of the objective function of this model is to minimize the total cost which is composed of several components: "material transportation cost between the relevant site facilities and the dismantling, setup and relocation costs for all of the involved site facilities in each construction stage" (Huang and Wong 2015). This model minorly took safety into considerations by allowing for minimum safety separating distance between facilities (Huang and Wong 2015). To test and verify the mathematical model generated, examples with a verity of nature (static and dynamic) were solved using the model (Huang and Wong 2015).

## Research gap and research questions

From the above discussed literature review, it can be concluded that, for modern construction site layouts to be optimized, four factors should be taken into considerations; related costs, related travel/relocation time, related risks and the dynamic environment of the construction site (majorly, project stages). It can be seen that there is a gap of combining three of these in depth, and thus, all four factors together in one holistic model that optimizes cost, time and risks in a dynamic presence. Therefore, this paper aims to fill this gap by developing such a model. In this paper, the aim is to generate an optimization model that takes into account three of those factors with deep involvement; cost, risk and dynamic environment. This may not seem to be an easy task and thus there should be several research questions in mind. Such research questions may include:

- What is the combined effect of optimizing cost and risk in a dynamic model?
- What might be some of the limitations of such a model?

Main contribution of the paper

This paper offers a contribution to project success and decision-making since it offers a unique model that fulfils the previously discussed research gap and allows for the optimization of cost and safety in a dynamic environment, which depicts real-life construction sites (Fig. 2). This is very important in saving time and cost in the project analysis and execution phases and completing the project with the highest degree of safety.

Fig. 2 Main contribution to research gap
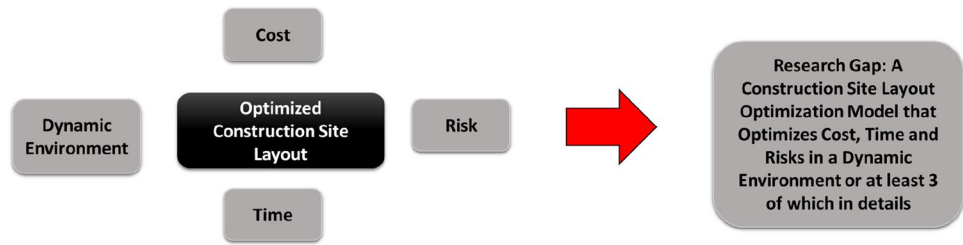
Research framework

The chart in Fig. 3 illustrates the planned research framework for this report.

Classification of aspects affecting a construction site optimization

This research is concerned with the construction industry and involves the study of the optimization of a construction site layout. Based on the previously carried out literature review, it has been found that there is a gap in having an optimization model that takes into account at least three of the four major elements of an optimized construction
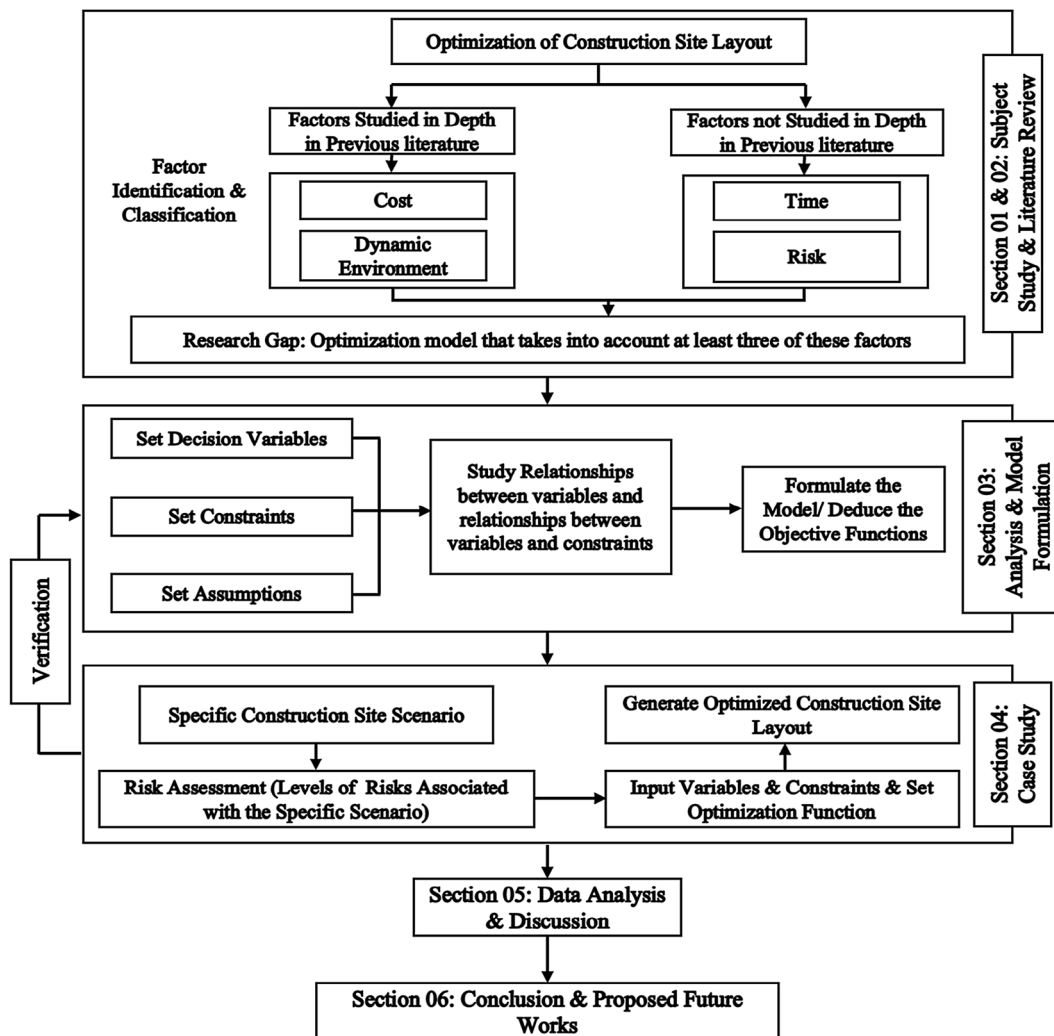

Fig. 3 Research framework

site layout: cost, time, risk and dynamic environment. This research aims to combine three of elements (cost, risk and dynamic environment) to generate a detailed optimized model of construction site layout. The previous chapter demonstrates that the following aspects affect the performance of a construction site layout:

- Types of risks involved
- Likelihood of each type of risk involved happening
- Severity of each type of risk involved
- Cost of fixing facilities
- Relocation cost of facilities
- Transportation costs of facilities
- Distance between locations of facilities
- Travel cost between facilities
- Size of facilities
- Type of facilities involved
- Sizes of available locations
- Flow of materials
- Flow of people
- Flow of equipment
- Number of construction stages

To generate an optimization model, the above aspects can be classified into: variables, constraints, element to be optimized and assumptions.

Variables

The following are the proposed decision variables, each with its own symbol (abbreviation). Symbols will be used as means of reference to variables throughout the paper. Variables include:

- F_i, F_{ii}: Facility to be allocated (for instance: site offices, storage area and batching plant will have the symbols of $F1$, $F2$ and $F3$, respectively).
- L_j, L_{jj}: Available locations for facilities to be allocated ($L1$, $L2$, $L3$, etc. refer to available location 1, available location 2, available location 3, etc.)
- F_{total}: Total number of facilities to be allocated.
- L_{total}: Total number of available locations for facility allocation.
- T_{total}: Total number of project stages.
- M: Material type.
- M_{total}: Total number of material types.
- t: Construction stage.
- $LengthF_{it}$: Length of facility i during construction stage t.
- $WidthF_{it}$: Width of facility i during construction stage t.
- $LengthL_{jt}$: Length of available location j during construction stage t.

- $WidthL_{jt}$: Width of available location j during construction stage t.
- $LengthSZ_{it}$: Length of safety zone for facility i during construction stage t.
- $WidthSZit$: Width of safety zone for facility i during construction stage t.
- FC_i: Fixing/setup cost of facility i.
- RC_i: Relocation cost of facility i, (AED/m).
- DC_i: Dismantling cost of facility i from site.
- RFF_{it}: Rating/level of risk associated with fixing/setting up facility i during construction stage t.
- RRF_{it}: Rating/level of risk associated with relocating facility i during construction stage t.
- RDF_{it}: Rating/level of risk associated with dismantling facility i during construction stage t.
- M_{Miiit}: Amount of material M flowing from facility i to facility ii during construction stage t.
- RM_M: Rating/level of risk associated with material M.
- MC_M: Unit cost of transporting material M.
- E: Equipment type.
- E_{total}: Total number of equipment types.
- E_{Eiiit}: Number of equipment E flowing from facility i to facility ii during construction stage t.
- EC_E: Unit cost of moving equipment E.
- RE_E: Rating/level of risk associated with equipment E.
- P_{iiit}: Number of people flowing from facility i to facility ii during construction stage t.
- PC: Unit cost of moving one person.
- RP_{iiit}: Rating/level of risk associated with people flow.
- $SD_{i,ii,t}$: Minimum safety distance between facility i and facility ii during construction stage t.
- $StatusF_{it}$: Input binary variable, where "1" means that facility i exists during construction stage t and "0" if not.
- $StatusL_{jt}$: Input binary variable, where "1" means that location j is available for a facility to be set up during construction stage t and "0" if not.
- X_{ijt}: Binary variable, where "1" means that facility i is to be allocated in available location j during construction stage t and "0" if not.
- $Y_{ijjjt,t+1}$: Binary variable, where "1" means that facility i is allocated to available location j during construction stage t and another available location jj during the next construction stage $t+1$ and "0" if not.
- SUF_{it}: Binary variable, where "1" means that facility i will be set up at the end of stage t, and "0" if not.
- DF_{it}: Binary variable, where "1" means that facility i will be dismantled at the end of stage t, and "0" if not.
- $DL_{j,jjt}$: Distance between available locations j and jj during construction stage t.
- $Z_{i,j,ii,jj,t}$: Binary variable, where "1" means that facility i will be set up in available location j and another facility ii will be set up in another available location jj during construction stage t and "0" if not.

Constraints

The following constraints are to be considered:

Facility setup in available locations and overlap constraints: this is to prevent physical overlap between facilities or any duplication of facilities (having more than one facility assigned to the same location). The equation for this constraint can be formulated as follows:

$$\sum_{i=1}^{F_{total}} X_{ijt} \leq Status L_{jt} \quad \forall j, t, \tag{1}$$

$$\sum_{j=1}^{L_{total}} X_{ijt} = Status F_{it} \quad \forall i, t. \tag{2}$$

The above equations ensure that facility i exists in construction stage t and location j is available in construction stage t to enable facility i to be allocated in location j during construction stage t avoiding any duplications of facilities in the same location. In Eq. 1, if L_{jt} is "1" that means there is an available location "L_j" during the construction stage t and the available location can either stay empty or be occupied only by one facility; X_{ijt} can be either assigned "0" or "1". In the case of L_{jt} being "0", which means that the location is unavailable, X_{ijt} is forced to be assigned "0" as well. In Eq. 2, if F_{it} is "1", this means that facility F_i is required in construction stage t and X_{ijt} is forced to be "1" and Facility F_i should be placed in one of the available locations.

The size of the facility should be less than the available location size in order for it to fit inside the location. Furthermore, the safety zone around each facility should be a part of the facility's size in such a calculation. To be more specific, the safety zone around the facility, along with the facility size, both should add up to a size less than or equal to that of the available location during construction stage t in order for the facility to be allocated in the available location. The following equations illustrate this in numbers:

$$X_{ijt}\left(Length L_{jt} - Length F_{it}\right) \geq Length SZ_{it} \quad \forall i, j, t, \tag{3}$$

$$X_{ijt}\left(Width L_{jt} - Width F_{it}\right) \geq Width SZ_{it} \quad \forall i, j, t. \tag{4}$$

In Eq. 3, length of available location L_j during construction stage t minus length of facility F_i during construction stage t should be less than or equal to the length of safety zone required during construction stage t. In this case, X_{ijt} can be assigned either "1" or "0"; available location L_j is one of the choices in which facility F_i can be allocated. In the case of having a safety zone length less than the length of available location during construction stage t minus the length of facility F_i during construction stage t, X_{ijt} is forced to become "0" to satisfy the constraint. Equation 4 illustrates

the same but, for the width of facility, location and safety zone.

The binary variable $Z_{i,j,ii,jj,t}$ illustrates the link between facility F_i in location j and facility F_{ii} in location jj. In Eq. 5, for the link to be established between both facilities ($Z_{i,j,ii,jj,t}$ is "1"), both X_{ijt} and X_{iijjt} should be "1". On the other hand, if either or both of X_{ijt} and X_{iijjt} is "0", $Z_{i,j,ii,jj,t}$ is forced to be zero by Constraint Eqs. 6 and 7. These constraints come in handy when dealing with variables related to materials, equipment and people flow. Table 1 shows combinations of these constraints.

$$2 - X_{ijt} - X_{iijjt} \geq 1 - Z_{i,j,ii,jj,t} \quad \forall i, ii, j, jj, t, i \neq ii, j \neq jj \tag{5}$$

$$X_{ijt} \geq Z_{i,j,ii,jj,t} \quad \forall i, ii, j, jj, t, i \neq ii, j \neq jj \tag{6}$$

$$X_{iijjt} \geq Z_{i,j,ii,jj,t} \quad \forall i, ii, j, jj, t, i \neq ii, j \neq jj. \tag{7}$$

At the transition between construction stages, it should be decided whether a certain facility is to be setup or dismantled. In Eq. 8, DF_{it} is forced to be 1 if $Status F_{it}$ is 1 and $Status F_{it+1}$ is zero, meaning that the facility is to be dismantled before the start of stage $t+1$. If the facility is to be there in both stages t and $t+1$, that is $Status F_{it}$ and $Status F_{it+1}$ are both "1", DF_{it} is forced to become zero and facility i is not to be dismantled. Similarly, in Eq. 9, SUF_{it} is forced to be 1 if $Status F_{it}$ is zero and $Status F_{it+1}$ is 1, meaning that the facility is to be setup before the start of stage $t+1$.

$$1 - Status F_{it} + Status F_{it+1} \geq 1 - DF_{it} \quad \forall i, t \in \{1, T-1\} \tag{8}$$

$$1 - Status F_{it+1} + Status F_{it} \geq 1 - SUF_{it} \quad \forall i, t \in \{1, T-1\}. \tag{9}$$

To ensure safety on site, the safety distance between facilities should be satisfied. To apply this, the distance between available locations should be greater than or equal to the specified safety distance between facilities. This translates to Eq. 10. $Z_{i,j,ii,jj,t}$ is forced to become "0" if the safety distance between facilities is more than the distance between available locations, and thus, facilities i and ii cannot be placed in locations j and jj, respectively. In the case of the constraint being satisfied and $Z_{i,j,ii,jj,t}$ is

Table 1 Combinations of Constraints 5, 6 and 7

Decision Variables		$Z_{i,j,ii,jj,t}$		
X_{ijt}	X_{iijjt}	Constraint 5	Constraint 6	Constraint 7
0	0	0 or 1	0	0
0	1	0 or 1	0	0 or 1
1	0	0 or 1	0 or 1	0
1	1	1	0 or 1	0 or 1

assigned to "1", locations j and jj can be regarded as possible locations for facilities i and ii, respectively.

$$Z_{i,j,ii,jj,t}\left(\mathrm{DL}_{j,jjt} - \mathrm{SD}_{i,ii,t}\right) \geq 0 \; \forall i, ii, j, jj, t, i \neq ii, j \neq jj. \quad (10)$$

Since the optimization problem in this paper is to take into account the dynamic environment of a construction site, some constraints should be set to define whether a facility is to be set up in different locations at each stage. In Eq. 11, if facility i is setup in location j during construction stage t and in location jj in constriction stage $t+1$, then both X_{ijt} and $X_{ijj,t+1}$ are "1", and therefore, $Y_{ijjjt,t+1}$ is forced to be "1". In Eqs. 12 and 13, $Y_{ijjjt,t+1}$ is forced to be assigned "0" if either of X_{ijt} or $X_{ijj,t+1}$ is "0". Table 2 shows combinations of these constraints.

$$2 - X_{ijt} - X_{ijj,t+1} \geq 1 - Y_{ijjjt,t+1} \quad \forall i, j, jj, t \in \{1, T-1\}, j \neq jj, \quad (11)$$

$$X_{ijt} \geq Y_{ijjjt,t+1} \quad \forall i, j, jj, t \in \{1, T-1\}, j \neq jj, \quad (12)$$

$$X_{ijj,t+1} \geq Y_{ijjjt,t+1} \quad \forall i, j, jj, t \in \{1, T-1\}, j \neq jj. \quad (13)$$

Objective function

The objective function in this paper aims to minimize costs and risks in the dynamic environment of a construction site layout. The optimization function is to be a multi-objective function. That is, there will be two objective functions: one aims to minimize costs involved and the other aims to minimize risks involved. Both equations are set to be in a dynamic construction site environment. The costs involved in the cost objective function include: material transportation costs, relocation of facilities during different construction stages, setting up facilities, dismantling facilities, equipment movement costs and people moving costs. In addition, the risks involved in the risks objective function include: risks due to material flow, risks due to facility relocation, risk due to facility setup, risk due to facility dismantling, risks due to equipment flow and risks due to human flow,

Table 2 Combinations of Constraints 11, 12 and 13

Decision variables		$Y_{ijjjt,t+1}$		
X_{ijt}	$X_{ijj,t+1}$	Constraint 11	Constraint 12	Constraint 13
0	0	0 or 1	0	0
0	1	0 or 1	0	0 or 1
1	0	0 or 1	0 or 1	0
1	1	1	0 or 1	0 or 1

For the cost objective function, the following functions are used and added together to bring about the overall cost objective function.

First is cost of material transport within the site for all construction stages (Eq. 14).

$$C1 = \sum_{F_i=1}^{F_{\mathrm{total}}} \sum_{j=1}^{L_{\mathrm{total}}} \sum_{F_{ii}=1}^{F_{\mathrm{total}}} \sum_{L_{jj}=1}^{L_{\mathrm{total}}} \sum_{M=1}^{M_{\mathrm{total}}} \sum_{t=1}^{T_{\mathrm{total}}} Z_{i,j,ii,jj,t} M_{Miiit} \mathrm{MC}_M \mathrm{DL}_{j,jjt} \; . \quad (14)$$

Second is cost of facility relocation within the project construction stages (Eq. 15).

$$C2 = \sum_{F_i=1}^{F_{\mathrm{total}}} \sum_{j=1}^{L_{\mathrm{total}}} \sum_{jj=1}^{L_{\mathrm{total}}} \sum_{t=1}^{T_{\mathrm{total}}} Y_{ijjjt,t+1} \mathrm{RC}_i \mathrm{DL}_{j,jjt} \; . \quad (15)$$

Third is cost of dismantling facilities within the project construction stages (Eq. 16).

$$C3 = \sum_{i=1}^{F_{\mathrm{total}}} \sum_{t=1}^{T_{\mathrm{total}}} \mathrm{DC}_i \mathrm{DF}_{it}. \quad (16)$$

Fourth is cost of setting up facilities within the project construction stages (Eq. 17).

$$C4 = \sum_{F=1}^{F_{\mathrm{total}}} \sum_{t=1}^{T_{\mathrm{total}}} \mathrm{FC}_i \mathrm{SUF}_{it}. \quad (17)$$

Fifth is cost of moving equipment between facilities within all construction stages (Eq. 18).

$$C5 = \sum_{F_i=1}^{F_{\mathrm{total}}} \sum_{L_i=1}^{L_{\mathrm{total}}} \sum_{F_{ii}=1}^{F_{\mathrm{total}}} \sum_{L_{jj}=1}^{L_{\mathrm{total}}} \sum_{E=1}^{E_{\mathrm{total}}} \sum_{t=1}^{T_{\mathrm{total}}} Z_{i,j,ii,jj,t} E_{Eiiit} \mathrm{EC}_E \mathrm{DL}_{j,jjt} \; . \quad (18)$$

Sixth is cost of moving people between facilities within all construction stages (Eq. 19).

$$C6 = \sum_{F_i=1}^{F_{\mathrm{total}}} \sum_{L_i=1}^{L_{\mathrm{total}}} \sum_{F_{ii}=1}^{F_{\mathrm{total}}} \sum_{L_{jj}=1}^{L_{\mathrm{total}}} \sum_{t=1}^{T_{\mathrm{total}}} Z_{i,j,ii,jj,t} P_{iiit} \mathrm{PC} \, \mathrm{DL}_{j,jjt} \; . \quad (19)$$

The overall cost objective function can be combined to result in Eq. 20.

Minimize $(C1 + C2 + C3 + C4 + C5 + C6)$. $\quad (20)$

For the risk objective function, the following functions are used and added together to bring about the overall risk objective function.

First is risk of material transport within the site for all construction stages (Eq. 21).

$$R1 = \sum_{F_i=1}^{F_{\mathrm{total}}} \sum_{L_i=1}^{L_{\mathrm{total}}} \sum_{F_{ii}=1}^{F_{\mathrm{total}}} \sum_{L_{jj}=1}^{L_{\mathrm{total}}} \sum_{M=1}^{M_{\mathrm{total}}} \sum_{t=1}^{T_{\mathrm{total}}} Z_{i,j,ii,jj,t} M_{Miiit} \mathrm{RM}_M \mathrm{DL}_{j,jjt} \; . \quad (21)$$

Second is risk of Facility relocation within the project construction stages (Eq. 22).

$$R2 = \sum_{F=1}^{F_{\text{total}}} \sum_{t=1}^{T_{\text{total}}} Y_{ijjjt,t+1} \text{RRF}_{it} \text{DL}_{j,jjt} \tag{22}$$

Third is risk of dismantling facilities within the project construction stages (Eq. 23).

$$R3 = \sum_{L=1}^{F_{\text{total}}} \sum_{t=1}^{T_{\text{total}}} \text{RDF}_{it} \text{DF}_{it,t+1} . \tag{23}$$

Fourth is risk of setting up facilities within the project construction stages (Eq. 24).

$$R4 = \sum_{F=1}^{F_{\text{total}}} \sum_{t=1}^{T_{\text{total}}} \text{RFF}_{it} \text{SUF}_{it,t+1} . \tag{24}$$

Fifth is risk of moving equipment between facilities within all construction stages (Eq. 25).

$$R5 = \sum_{F_i=1}^{F_{\text{total}}} \sum_{L_i=1}^{L_{\text{total}}} \sum_{F_{ii}=1}^{F_{\text{total}}} \sum_{L_{jj}=1}^{L_{\text{total}}} \sum_{E=1}^{E_{\text{total}}} \sum_{t=1}^{T_{\text{total}}} Z_{i,j,ii,jj,t} E_{Eiiit} \text{RE}_E \text{DL}_{j,jjt} . \tag{25}$$

Sixth is risk of moving people between facilities within all construction stages (Eq. 26).

$$R6 = \sum_{F_i=1}^{F_{\text{total}}} \sum_{L_i=1}^{L_{\text{total}}} \sum_{F_{ii}=1}^{F_{\text{total}}} \sum_{L_{jj}=1}^{L_{\text{total}}} \sum_{t=1}^{T_{\text{total}}} Z_{i,j,ii,jj,t} P_{iiit} \text{RP}_{iiit} \text{DL}_{j,jjt} . \tag{26}$$

The overall risk objective function can be combined to result in Eq. 27.

$$\text{Minimize } (R1 + R2 + R3 + R4 + R5 + R6). \tag{27}$$

Assumptions

The following assumptions are to be considered:

- Shape of facilities is to be rectangular or square; dimensions are to be in the form of length × width measured in meters.
- Shape of available locations is to also be rectangular or square; dimensions are to be in the form of length x width measured in meters.
- Fixing and dismantling of a facility are expected to be carried out immediately from one construction stage to the next.
- Each available location is allowed to be occupied by only one facility at a time.

Tool to be used

Based on the literature reviewed carried out previously, there are several tools and techniques, which were used to optimize a construction site layout. These techniques include: genetic algorithm (GA), approximate dynamic programming (ADP), ant colony, neural networks and linear programming.

In this paper, MATLAB was the targeted software for use, but unfortunately, was unable to handle the model since the number of variables turned out to be huge. Therefore, another software, called LINGO, which is a specialized tool for optimization, was used to solve the model. Using LINGO software, the model optimization was carried out by means of a standard branch-and-bound technique. It should be noted that other techniques were also given a try, but unfortunately were taking a very long time for the model to run or were not running. As a result, the standard branch-and-bound technique using LINGO software was found to be the most suitable in terms of both running time and model complexity.

Case study

To demonstrate the generated model, a numerical example of an existing construction site is to be solved. The real-life example is a project held in Dubai that had no optimization performed for its construction site layout; some cost considerations were however, taken into account. The dynamic environment of this project is to depict what exactly happened in the project's construction site in reality. The dynamic scenario differs from the static one in that it takes into account the relocation of facilities. In a dynamic layout, any changes in the site space are considered and newly added facilities have the chance to compete for any of the already filled locations if that is to optimize cost and risk. In a static case, however, the only available locations can be occupied by newly added facilities; the possible reuse of locations to accommodate facilities through different stages is ignored within a static environment. The dynamic layouts generated from the optimization model are to be compared with the situation in reality in terms of both cost and risk to see the difference that the optimization model can generate.

The materials considered in this case study are concrete (aggregates, sand and cement), steel rebars, formwork and façade panels. It should be noted that these are the major materials used in the project in real-life in addition to several others. But, for the sake of simplicity, only these four materials are to be considered in this optimization problem. Material transportation unit cost is assumed to be based on the material weight. In this problem, material costs and flow frequencies are input variables.

In this example, there are ten available locations and ten facilities to be allocated, each in one of the available locations. For the dynamic part of this problem, sizes of both; available locations and facilities, may differ from one construction stage to the next. As the project proceeds, less areas become available and some facilities get smaller. Some facilities may even be no longer needed and some locations may be no longer be available. The number of construction stages in this example is two; in which the objective is to optimize the cost and risk of facility allocation over the available locations (refer to Appendix file for data related to stage 1 and 2).

In this case study, the model was run for two scenarios: optimizing cost only and optimizing both cost and risk together. LINGO was used to solve the proposed model according to the inputs from the provided case study. The output of the model is the optimized allocation of each facility based on the minimum cost and risk in the first scenario and on minimum cost only in the second. The second scenario is majorly done to compare to the real-life situation in which there were no risks considered; that is, to see how much more the model can optimize when the cost is given the full optimization weight. Risk is, however, calculated for the real-life scenario based on the allocation decided and compared, along with cost, with the first scenario generated by the model to have a full image of the comparison as a whole. The reports generated from LINGO are in thousands of pages. Nevertheless, certain variables can be chosen to be shown on shorter reports. The shorter generated reports are chosen to show, in nonzero values, the values of $C1$, $C2$, $C3$, $C4$, $C5$, $C6$, $R1$, $R2$, $R3$, $R4$, $R5$, $R6$, X, Y, Z and statuses of facilities and locations to ensure inputs are on the right track.

The results shown in Table 3 show the optimized solution of allocating facilities, which can be interpreted for the first scenario (optimized cost and risk).

Data analysis and discussion

This section illustrates the calculations that led to the final total cost and risk and thus the final allocation of facilities for the real-life situation. Since no optimization was done for the real-life situation, calculations had to be done to find the final total cost and risk of the allocation carried out. The below section demonstrates the cost and risk calculations of the real-life scenario performed on site. In order to be able to carry out the comparison between both situations (will be done in Sect. 5.5 of this paper), the real-life facility allocation should be first showed. It should be noted however that the real-life situation was done based on experience and some cost considerations, but none from the risk point of view. Therefore, the results compared in this section of the paper are concerned with comparing the final total cost and risk (scenario 1 of the model) with real-life situation and comparing scenario 2 of the model (only cost optimization) with the real-life scenario since cost was partially considered when allocating facilities in the actual site.

Comparison between the model results and reality

This section of the paper demonstrates a comparison between the scenarios tested and the real situation that occurred on site. The final cost and risk assessment, however, of the project in real life was calculated and is compared here within with the results of the model used in this paper. The total facility setup cost is that of setting up facility 9 at the end of stage 1, before stage 2 begins. Dismantling cost is only calculated for facility 10 at the end of stage 1, before stage 2 begins. The relocation costs are considered only for facilities 6 and 8 before the start of stage 2. For the results generated by the model, the total cost/risk

Table 3 Results of solving the case study using the proposed model

Facility, F_i	Scenario 1 (optimization of cost and risk)		Scenario 2 (optimization of cost only)	
	Location in Stage 1	Location in Stage 2	Location in Stage 1	Location in Stage 2
($F1$) Main gate	$L7$	$L7$	$L7$	$L7$
($F2$) Steel storage area	$L2$	$L2$	$L2$	$L2$
($F3$) Formwork storage area	$L1$	$L10$	$L1$	$L1$
($F4$) Steel bar bending area	$L4$	$L4$	$L4$	$L4$
(F5) Steel bar cutting area	$L9$	$L9$	$L9$	$L9$
($F6$) Batching plant	$L8$	$L8$	$L8$	$L8$
($F7$) Concrete components storage area (aggregates, sand and cement)	$L5$	$L5$	$L5$	$L5$
($F8$) Site offices	$L6$	$L3$	$L6$	$L3$
($F9$) Façade panel storage	Facility does not exist	$L1$	Facility does not exist	$L10$
($F10$) secondary gate	$L3$	Facility does not exist	$L3$	Facility does not exist

is calculated for both project stages together, unlike that of the real situation (calculated for each stage alone since it was done manually). Therefore, the values for both stages should be added together to be compared with the model results. Figures 4 and 5 illustrate the real-life scenario in both stages 1 and 2, Figs. 6 and 7 illustrate the generated
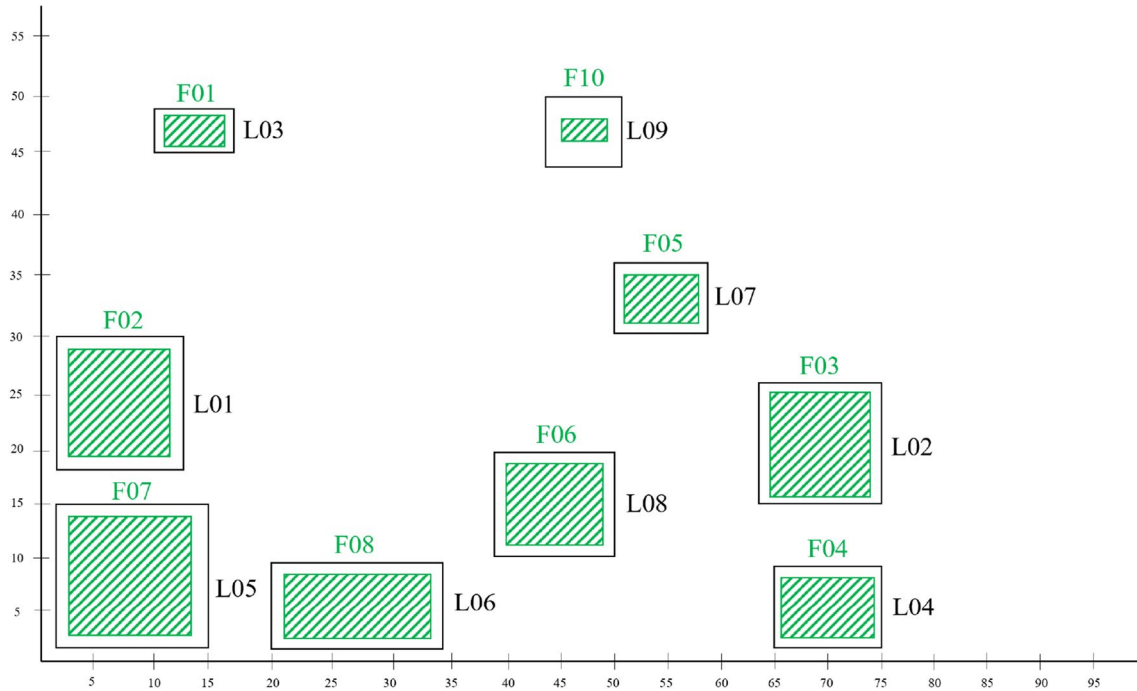

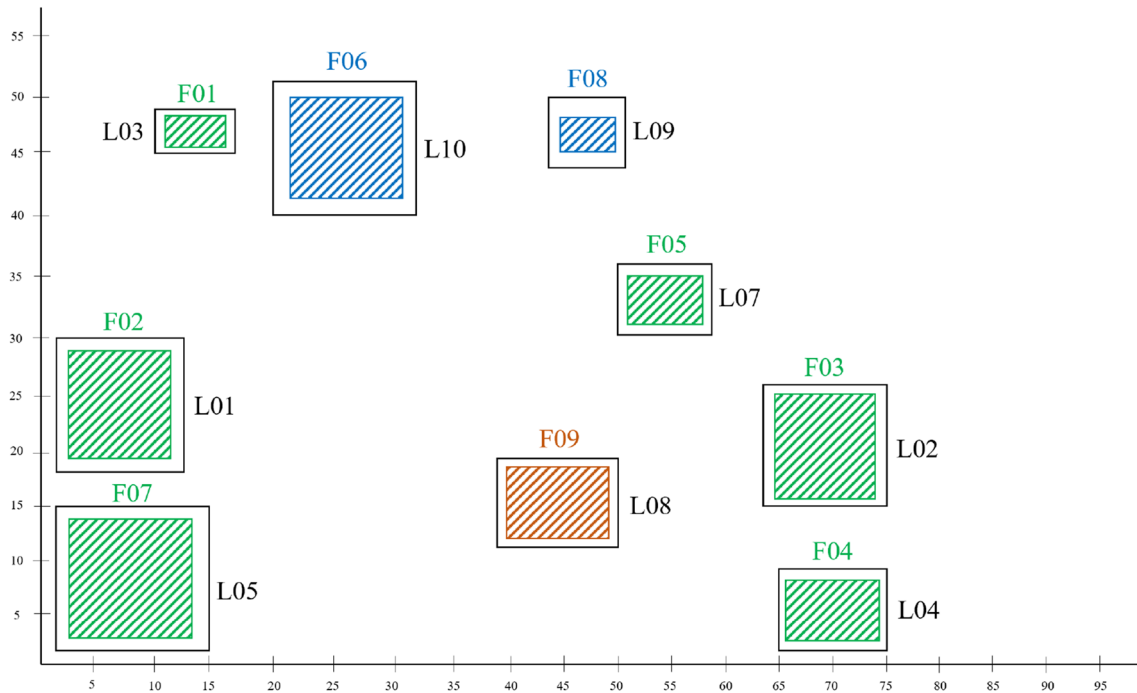**Fig. 4** Illustration of real-life allocations for stage 1
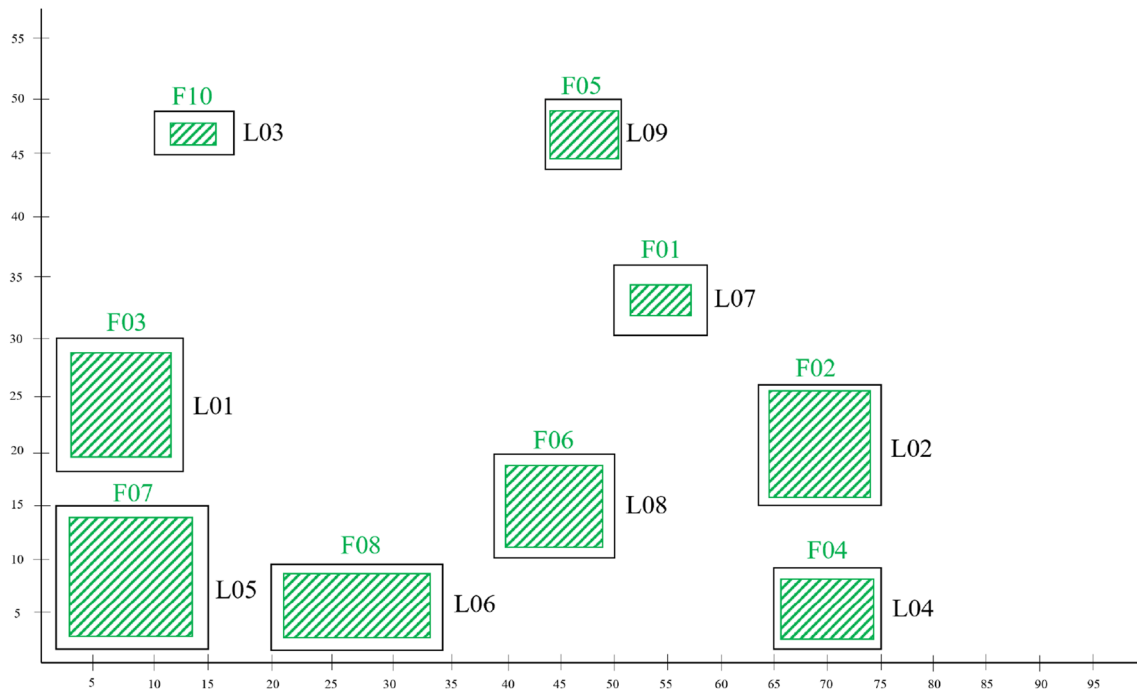

Fig. 5 Illustration of real-life allocations for stage 2

Fig. 6 Illustration of optimized allocations for scenario 1 in stage 1
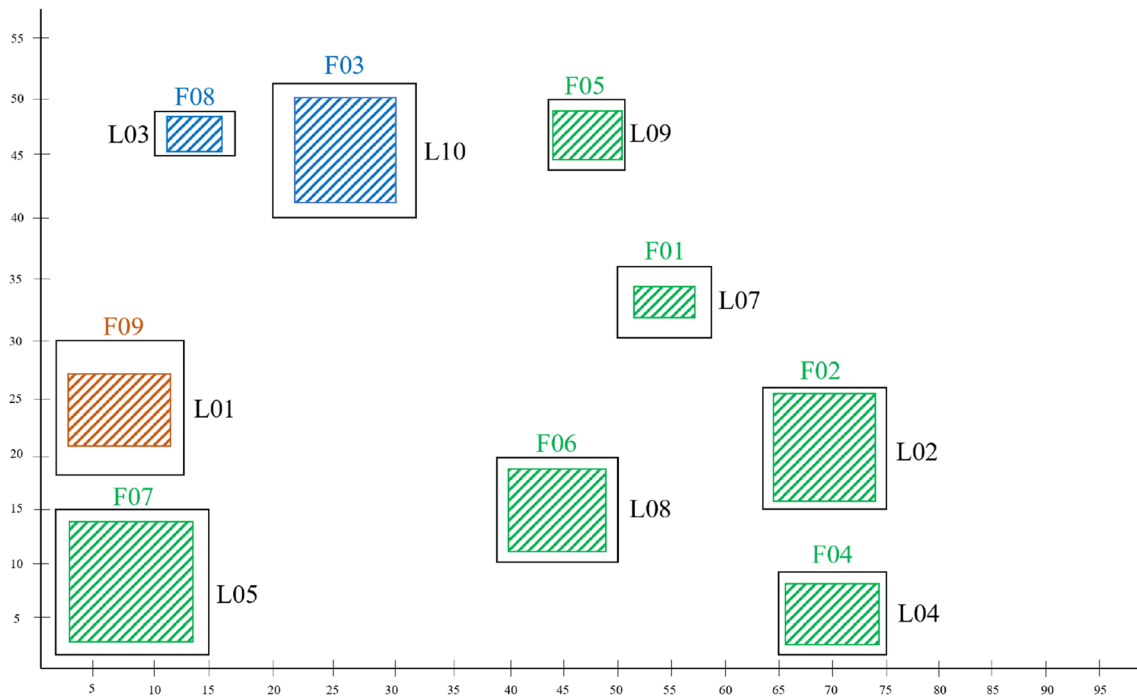

Fig. 7 Illustration of optimized allocations for scenario 1 in stage 2

optimized model results for scenario 1 in both stages 1 and 2, and Figs. 8 and 9 illustrate the generated optimized model results for scenario 2 in both stages 1 and 2 (Table 4).

Figures 4 and 5 illustrate the allocation of facilities in both stages; 1 and 2 for the real-life scenario. The facilities hatched in green are those that remain in the same location
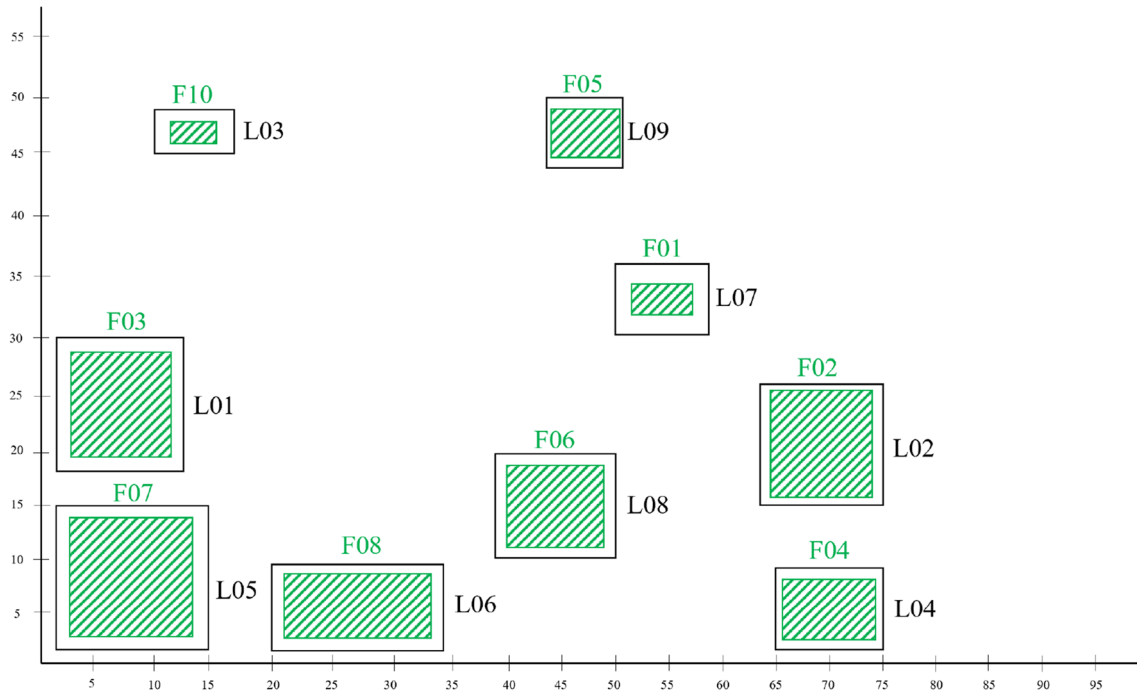
Fig. 8 Illustration of optimized allocations for scenario 2 in stage 1
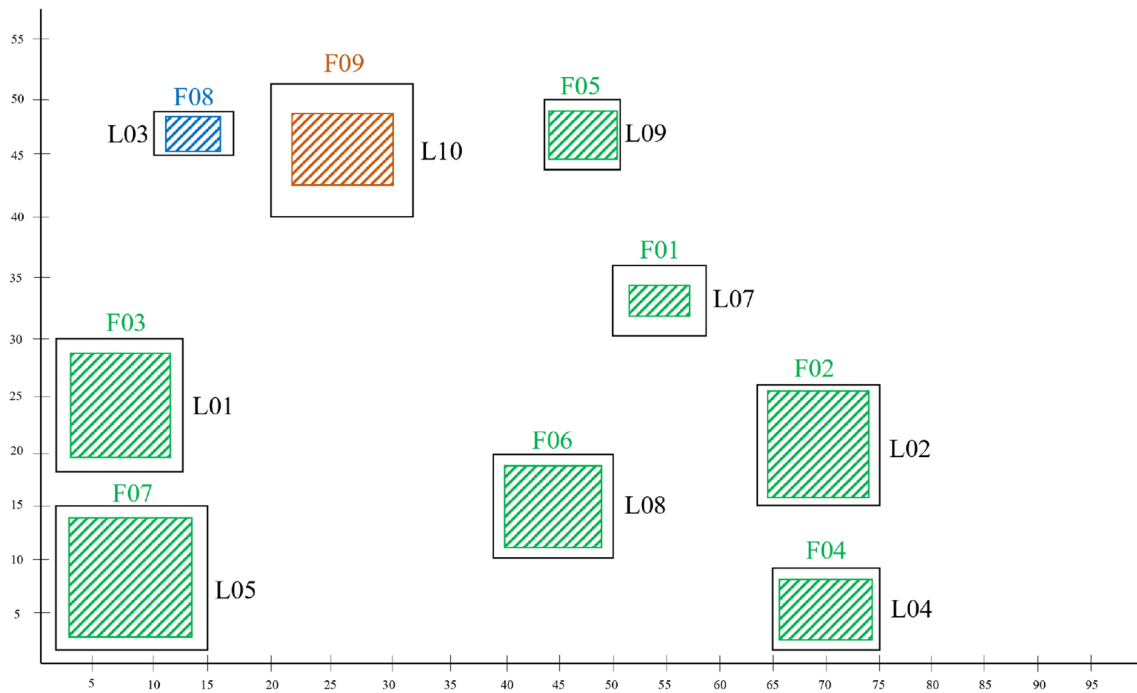

Fig. 9 Illustration of optimized allocations for scenario 2 in stage 2

in both stages, while the ones in blue are those that are relocated and the ones in orange are the ones newly setup before the start of stage 2. Since facility 10 was dismantled at the

end of stage 1, location 9 becomes free in stage 2. In addition, location 6 no longer exists in stage 2 and facility 9 is newly fixed in stage 2. In light of these changes, facility 8

Table 4 Result comparison between real-life and optimized scenarios

	Real-life scenario		Optimized scenario 1 (risk and cost)		Optimized scenario 2 (cost only)	
	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2
Location of facilities 1–10	L3	L3	L7	L7	L7	L7
	L1	L1	L2	L2	L2	L2
	L2	L2	L1	L10	L1	L1
	L4	L4	L4	L4	L4	L4
	L7	L7	L9	L9	L9	L9
	L8	L10	L8	L8	L8	L8
	L5	L5	L5	L5	L5	L5
	L6	L9	L6	L3	L6	L3
	Facility does not exist	L8	Facility does not exist	L1	Facility does not exist	L10
	L9	Facility does not exist	L3	Facility does not exist	L3	Facility does not exist
Material transport cost (AED)	3010 5618	2608	4746.9		4728.2	
Equipment cost (AED)	7367 13,842	6475	9795.5		9863.5	
People transport cost (AED)	3109 6526	3417	5181.2		5188	
Facility relocation cost (AED)	5720	–	4800		2850	
Facility setup cost (AED)	9000	–	9000		9000	
Facility dismantle cost (AED)	8000	–	8000		8000	
Total optimized cost (AED)	48,706		41,523.6		39,629.7	
Optimized material risk	13,320 24,104	10,784	18,115.2		–	
Optimized equipment risk	19,968 37,706	17,738	26,422.3		–	
Optimized people transport risk	30,250 58,312	28,062	50,947.8		–	
Optimized facility relocation risk	209.5	–	121.2		–	
Optimized facility setup risk	1	–	1		–	
Optimized facility dismantle risk	0.4	–	0.4		–	
Optimized total risk	120,333		95,607.9		–	

was decreased in size (project requirement) and relocated from location 6 (removed in stage 2) to location 9 (free in stage 2 since facility 10 is dismantled). Furthermore, facility 6 was increased in size in stage 2 and thus, had to be relocated; it was relocated to location 10 (location got to be available in stage 2). Finally, location 8 becomes available and the newly added facility (facility 9) is setup in location 8.

Figures 6 and 7 illustrate the allocation of facilities resulted from the model optimization for scenario 1 (optimizing cost and risk). Similarly, the facilities hatched in green are those that remain in the same location in both stages while the ones in blue are those that are relocated and the ones in orange are the ones newly setup before the start of stage 2. Figure 6 shows the allocation of facilities in stage 1 of this scenario, while Fig. 7 shows the same for stage 2 where facility 10 is dismantled, facility 9 is setup, facility 3 is relocated from location 1 to location 10 (which becomes available only at stage 2) and facility 8 is relocated from location 6 to location 3 (which becomes available after dismantling facility 10 that used to occupy it). Finally, Figs. 8 and 9 show the allocation of optimized results for the second scenario (optimizing cost only). Figure 8 shows the allocation of facilities in stage 1 of this scenario, while Fig. 9 shows the same for stage 2 where facility 10 is dismantled, facility 9 is setup and facility 8 is relocated from location 6 to location 3 (which becomes available after dismantling facility 10 that used to occupy it).

Discussion of results

In order to make sense of how much this model can optimize a site layout, the results generated by the model in both scenarios should be compared with the real-life situation carried out on site.

To start, running scenario 1 of the model show the results of optimizing both; cost and risk. In the real-life scenario, the total cost associated with the allocation was calculated to be AED 48,706. Comparing this value to the optimized cost generated by the model in scenario 1 (AED 41,523.6) shows that there is approximately 15% decrease in the total cost of the facility allocation. In addition to that, comparing the individual costs, each by its corresponding in both cases, shows that the model also generates a decreased individual material, equipment, people flow and facility allocation costs. The cost of dismantling and setting up facilities, however, are the same since the same facilities are to be setup/dismantled in both cases.

Furthermore, the calculated risk for the real-life scenario was found to be 120,333. Comparing this to the optimized value generated by the model (95,607.9) yields a decrease of 20.5% of the value of risk. Similarly, comparing the individual risks, each by its corresponding in both cases, shows that the model also generates a decreased individual material, equipment, people flow and facility allocation risks.

Finally, since the real-life situation was carried out only with cost considerations, the model was run to optimize only cost with no risk considerations to see the model impact on cost alone. In scenario 2 of the model, only cost was optimized, and the optimized cost was found to be AED 39,629.7. Hence, optimizing cost only (scenario 2) resulted in an approximate reduction of 19% when compared with the real-life situation.

It can also be seen that, when comparing the costs in both scenarios generated by the optimization model, the cost in scenario 2 was less than that in scenario 1. The reason for that is the model in scenario 1 is optimizing both; risks and costs equally and thus cost had to increase a bit to accommodate the optimization in risks.

Therefore, the model has optimized both costs and risk considerably and is proven to be very handy to ensure both; saving money and having a safe environment on site.

Conclusion and future works

The objective of this paper is to optimize the construction site layout in terms of cost and risks taking into considerations that a site is a dynamic environment. The proposed model deals with the dynamic environment by considering project stages and facility relocations. The model proposed includes the costs and risks related to materials, equipment, people flow, facility setup, facility dismantling and facility relocation. The model is multi-objective with linear objective functions and linear constraints. It was run and results were proven successful with a significant decrease in both cost and risk values. This was illustrated by comparing the model results with a real-life situation that was carried out on the actual site.

In conclusion, for future research regarding this topic, it would be a great idea to include time as a factor to take this model an extra step towards having a holistic objective function that includes the optimization of cost, risk and time within the dynamic environment of a construction site. Another recommendation is to link such a model to building information modelling, BIM. This can allow better visualization and improve coordination and communication throughout both the preconstruction and construction stages.

Compliance with ethical standards

Conflict of interest The authors whose names are listed certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership or other equity interest; and expert testimony or patent-licensing arrangements) or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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