Site Layout and Construction Plan Optimization Using an Integrated Genetic Algorithm Simulation Framework

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Abstract

Efficiency of a planned site layout is essential for the successful completion of construction projects. Despite considerable research undertaken for optimizing construction site layouts, most models developed for this purpose have neglected the mutual impacts of the site layout and construction operation variables, and are not able to thoroughly model these impacts. This paper outlines a framework enabling planners to plan for site layout variables (i.e., size, location and orientation of temporary facilities), and construction plan variables (e.g., resources and material delivery plan), and simultaneously optimize them in an integrated model. In this framework, genetic algorithm (GA) and simulation are integrated; GA heuristically searches for the near-optimum solution with minimum costs by generating feasible candidate solutions, and simulation mimics construction processes, and measures the project costs by adopting those candidate solutions. The contribution of this framework is the ability to capture the mutual impacts of site layout and construction plans in a unified simulation model, and optimize their variables in GA, which subsequently entails developing a more efficient and realistic plan. Applicability of the framework is presented in a steel erection project.

Key words: *Site layout planning, Construction planning, Simulation, Genetic Algorithm, Optimization.*

Introduction

Site layout planning (SLP) is mainly involved in identifying the suitable size and position of temporary facilities on construction sites. In construction projects, efficiency of the site layout is crucial because of its impacts on productivity and safety. However, conflicting objectives and dependency between influencing factors make SLP a complex task. Many studies have been conducted on SLP, the majority of which focused on how to find the optimum location of facilities considering different constraints such as travel cost, safety and environmental risks, accessibility, and planners' preferences. For optimization purposes, the objective of most SLP models is to minimize the sum of weighted distance function (SWDF) defined as $\sum w \times d$, which assigns weights to the significance or cost of the interactions between facilities. To determine the weights, two methods exist: 1) quantitative method, where the weights represent the cost per unit length ($/m) of the transportation between facilities (e.g., Zhang and Wang (2008)), and 2) qualitative method, where the weights represent subjective closeness rates between facilities (e.g., Elbeltagi et al. (2004)). The main drawback of the quantitative method is that it is difficult to determine the cost per unit length of transportation, and the drawback of the qualitative method is that the subjective weights cannot realistically reflect the actual transportation cost.

Safety is another constraint in SLP that affects the location of facilities. Falling objects Anumba and Bishop (1997), crane operation hazards, location of hazardous material storage, and travel route intersections El-Rayes and Khalafallah (2005) have been the major safety risks considered in existing SLP studies. Different approaches have been adopted to reduce the risk of these hazards, including: 1) qualitative approaches, which consider safety and environmental issues in determining subjective closeness weights in SWDF (e.g., Elbeltagi et al. (2004)), 2) quantitative approaches, which seek to identify a quantitative index for evaluating safety of sites (e.g., El-Rayes and Khalafallah (2005)), and 3) hard constraint approaches, which define safety considerations as closeness hard constraints (e.g., El-Rayes and Said (2009)). Hard constraints are discrete, which means that they are either satisfied or not, and planners aim to satisfy them.

In the literature, fewer studies have been undertaken to determine the optimum size of facilities, or integrate SLP with construction planning. For identifying the size of the facilities, the knowledge-based model (Elbeltagi and Hegazy, 2001) and some simplified dynamic profiles (Zouein and Tommelein, 2001) were proposed by researchers, though the accuracy of these methods is compromised, by their failure to capture the inherent dynamics of construction projects. Some recent studies have recognized the significance of the integration of SLP decisions with construction planning decisons, and attempted to optimize the location of the facilities and construction plan variables such as material procurement (Said and El-Rayes, 2011) and project schedule (Said and El-Rayes, 2013). These studies introduced new approaches in SLP; however, they only considered transportation tasks, and did not model the impact of facility location and size on the construction operations. They also overlooked the uncertainties inherent in construction projects. To address these drawbacks, simulation has been used in SLP. The simulation-based models developed to optimize the location of facilities substantiated the superiorities of simulation over the previous methods. Modeling construction uncertainties (RazaviAlavi and AbouRizk, 2013), considering resource interactions (Alanjari et al., 2014), quantifying the impact of facility size on the projects (RazaviAlavi and AbouRizk, 2015), and providing the planners with more information (e.g., total time in system, utilization and waiting time) (Smutkupt and Wimonkasame, 2009) were also reported as the primary advantages of using simulation in this area. In some of these models, such as Alanjari et al. (2014), Marasini et al. (2001) and Azadivar and Wang (2000), simulation was also integrated with heuristic optimization methods to find the near-optimum solutions. However, the existing simulation-based methods concentrated only on either sizing facility (e.g., RazaviAlavi and AbouRizk, (2015)), or optimizing facility location (e.g., Azadivar and Wang (2000)), and the variables pertinent to the construction plan have not been optimized in a unified model with site layout variables.

In summary, the following drawbacks are identified in many methods developed for SLP:

1) The methods using SWDF as an objective function attempted to minimize the transportation distance or transportation costs in the site layout, but the impact of site layout on the other aspects of the project, such as productivity and production rate, though significant, not taken into account. For instance, positioning a material storage facility far from the construction area may lead to late delivery of the material, and interruptions in the workflow, thereby reducing the production rate, and incurring extra project costs.

2) The existing methods, except for simulation-based methods, disregarded construction plan decisions, or considered them only in a reduced capacity. For instance, late delivery of the materials from one facility to another is not merely driven by the long transportation distance between the facilities. In this respect, the number of available material handlers and the availability of the material in the facility are the other drivers, but they are not accounted for in these methods.

3) Sizing facilities is one of the significant tasks in SLP, but it has been often overlooked, or its impacts on the project have not been properly quantified in the existing methods (except for the simulation-based methods). The sizes of some facilities such as cranes, office trailers and batch plants are predetermined based on their size specifications, while the sizes of other facilities such as material laydown areas and storages are variable and should be determined throughout SLP. In the current practice for SLP, the size of the variable facilities is determined based on experience, rule of thumb, and heuristics, which may entail underestimation or overestimation of the facility size. Underestimating the facility size causes lack of space within that facility, reduces the productivity and may incur extra costs to resolve problems, while overestimation of facility size incurs extra costs for mobilization, maintenance, and demobilization of that facility, and may cause space shortage for other facilities on congested sites. Therefore, overlooking the importance of properly sizing facilities can expose the project to loss of productivity and extra costs.

4) Most of the existing methods seek to optimize only the site layout plan, omitting optimization of the construction plan, even though these two activities are dependent. Ignoring this dependency may result in suboptimum site layout and construction plans.

Despite the fact that some past studies have attempted to partially address these drawbacks in their models as discussed earlier, a framework that is able to comprehensively address all the drawbacks in a unified model is still needed. This study aims to develop such framework and bridge these gaps by adopting GA as a heuristic optimization method and simulation as a modeling tool, integrated to find the most cost-efficient site layout and construction plan variables in a unified model. In the following sections, the research methodology and the case study are presented. The overall conclusion is drawn is the last section.

Methodology

The methodology of this research is composed of the following steps:

- Identifying the optimization variables;
- Developing the optimization module employing GA;
- Developing the cost evaluation module employing simulation; and
- Integrating GA with simulation.

The first step is to identify the optimization variables, which fall into two major categories: 1) site layout variables, and 2) construction plan variables.

In SLP, attributes of facilities (i.e., size, location and orientation) can be either predetermined (i.e., fixed) or variable. That is, different types of facilities may exist on the site: predetermined-sized or variable-sized facilities, predetermined-location or movable facilities, and predetermined-orientation or variable-orientation facilities. Thus, the variable attributes of the facilities are considered to be site layout variables that should be determined through optimization.

Construction plan variables can influence the site layout plan or be influenced by it. This study concentrates on construction logistics plan variables, which are related to material management, logistics and resource planning, such as the number of material handlers and the material delivery schedule.

The proposed framework consists of two modules: 1) the optimization module, and 2) cost evaluation module. The role of the optimization module is to heuristically search for the near-optimum solution and produce feasible solutions. The feasible candidate solutions contain the values of site layout and the construction plan variables identified in the first step. These values are selected from their search domain while satisfying the site layout constraints. In this study, genetic algorithm (GA) is employed as the optimization method. The cost evaluation module evaluates the efficiency of site layout and construction plan variables in terms of the project cost. To this end, simulation is utilized to model the construction process and estimate the cost of the project for the candidate solutions produced by the optimization module. Simulation is selected for this purpose due to its capabilities in considering dynamics and uncertainties inherent in construction projects, and modeling resources and complex interactions between different variables. In this framework, simulation and GA are then fully integrated. Fig. 1 (a) shows schematically the integration of simulation and GA. As seen in this figure, a simulation model is built based on the construction process information and cost data. Then, the simulation model receives the feasible candidate solutions as part of its inputs, which are outputs of GA, and evaluates the project cost as the fitness (objective) function of GA. Details of these processes are described in the next subsections.

Optimization module

The heuristic optimization method used in this study is GA, which is based on biology. In GA, chromosomes represent candidate solutions and consist of genes. Each gene represents the value of a variable to be optimized. That is, a chromosome is a string of genes containing the values of all optimization variables. The goodness of the chromosomes is measured by a fitness function. GA is initialized by randomly generating a set of chromosomes called population. Then, three main operations: selection, crossover and mutation are executed to search for the fittest chromosome, which has a highest/lowest (depending on minimizing or maximizing the fitness function) value of the fitness function. Two chromosomes are randomly selected for crossover. The fitter chromosomes have a higher chance of being selected. In crossover, some genes of the two chromosomes are randomly swapped. Finally, to counteract being trapped into a local optimum solution, mutation is executed by randomly altering the value of one or more genes. In each iteration of this process, a new generation of chromosomes is created and evaluated by the fitness function. Reaching the maximum number of generations is one of the common conditions to stop the iteration (see Mitchell (1999) for further information about GA).

In this study, a chromosome consists of two major blocks of genes allocated to site layout and construction plan variables. In the site layout block, minor blocks are designated to the variables of each facility (i.e., size, orientation and/or location). Fig.1 (b) depicts the major and minor blocks of a chromosome. The number of genes in each minor block depends on the type of the facilities, as discussed earlier. For instance, if a facility is predetermined-sized, movable-location and variable-orientation, its corresponding block has two genes representing its location and orientation. In the site layout block, the total number of minor blocks equals the total number of facilities. Similarly, the construction plan block has a number of genes corresponding to the construction plan variables.

The next step is to identify the search domain of the variables. For the site layout variables, the layout hard constraints and some assumptions are considered. The assumptions in the model are as follows:

- The shape of the facility is rectangular,
- Underlying gridlines are used to identify the potential locations for positing facilities,
- The orientation of facilities is limited to 0 and 90 degrees if it is variable, and
- The possible sizes of facilities should be defined by the planner if size is variable.

The underlying gridlines create grid cells that are the potential locations of facilities. Numbering the grid cells facilitates encoding the location of facilities in GA. For instance, if the grid cell #*i* is designated to the location of the facility F_j, the top left corner of the facilities identified with the coordinates of (RXF_j, RYF_j) will be placed on the top left corner of the grid cell identified with the coordinates of (RXC_i, RYC_i). Fig. 2 (a) demonstrates grid cells, a facility and site area, in which only the grid cells that are completely inside the site boundaries are assumed to be available for designating to facilities. The size of the grid cells can affect the optimization since very small grid cells increase the search domain and optimization run time, while very large grid cells reduce the accuracy. Grid cell size is determined by the planner based on the size of the site and facilities, the defined hard constraints, and desired accuracy and optimization run time.

Using the Cartesian Coordination system, and knowing the coordinates of the grid cell reference points based on their size, the coordinates of the centers and corners of the facilities can be found, as presented in Fig. 2 (b). These points are used for evaluating hard constraints.

The following hard constraints are considered for positioning facilities (El-Rayes and Said 2009):

- Being inside the site boundaries, which implies that the entire area of all facilities must be inside the site boundaries,
- Non-overlapping between facilities, which implies that no facilities can overlap,
- Minimum/maximum distance (D_{min}/D_{max}) between facilities, and
- Inclusion/exclusion of a facility in/from a specified area.

The first two constraints are general for all sites. The second two constraints are used for safety, environmental, accessibility and other planners' considerations determined specifically for each site. The distance can be measured between different points of the facilities for various types of constraints. For example, the maximum distance between facilities can be used to make sure that a crane has access to the material storage. This distance will be measured from the center of the crane to the farthest corner point of the storage. Another example is the minimum distance used for specifying safety distance between facilities, such as the crane and office trailer. It will be measured from the center of the crane to the closest point of the office trailer. An inclusion/exclusion area can be used to identify the desirable/undesirable areas for locating a facility from the planner's point of view. For instance, no facility should be located in the area allocated to the access road, or a planner may intend to position the parking in the area that is close to the site entrance. Fig. 3 exhibits the hard constraints considered in this study.

To evaluate satisfaction of these constraints, the following formulas are used:

- For being inside the boundary for each facility, satisfying both:
  - All edges of the facility do not have any intersections with any edges of the boundaries; and
  - A point of the facility (e.g., its center or reference point) is inside the boundary.
- For non-overlapping between two facilities, satisfying either:

$$RXF_{Xmin} + LXF_{Xmin} \leq RXF_{Xmax}; \text{ or} \tag{1}$$

$$RYF_{Ymin} + LYF_{Ymin} \leq RYF_{Ymax} \tag{2}$$

where LXF is the length of the facility along X axis, LYF is the length of the facility along Y axis, and between two facilities, F_{Xmin} is the facility with minimum RXF, F_{Xmax} is the facility with maximum RXF, F_{Ymin} is the facility with minimum RYF, and F_{Ymax} is the facility with maximum RYF.

Note: If the RXF values of two facilities are equal, the second equation must be satisfied, and if RYF values are equal, the first equation must be satisfied.

- For inclusion/exclusion of a facility in/from the Area A, satisfying both:
  - No edges of the facility have any intersections with edges of the area; and
  - A point of the facility (e.g., its top left corner) is inside/outside the area.
- Minimum/maximum distance (Dmin/max) between a point of Facility #j with the coordinates of (x_j, y_j) and a point of Facility #k with the coordinates of (x_k, y_k) using Euclidean method:

$$\text{Minimum Distance: } D_{min} \leq \sqrt{(x_j - x_k)^2 + (y_j - y_k)^2} \tag{3}$$

$$\text{Maximum Distance: } D_{max} \geq \sqrt{(x_j - x_k)^2 + (y_j - y_k)^2} \tag{4}$$

- Minimum distance (D_{min}) between edges of Facility #j and #k:

$$|CXF_j\text{-}CXF_k|\text{-}(LXF_j\text{+}LXF_k)/2 \geq D_{min} \text{ ; or} \tag{5}$$

$$|CYF_j\text{-}CYF_k|\text{-}(LYF_j\text{+}LYF_k)/2 \geq D_{min} \tag{6}$$

- Maximum distance (D_{max}) between edges of Facility #j and #k:

$$|CXF_j\text{-}CXF_k|\text{-}(LXF_j\text{+}LXF_k)/2 \leq D_{max} \text{ ; and} \tag{7}$$

$$|CYF_j\text{-}CYF_k|\text{-}(LYF_j\text{+}LYF_k)/2 \leq D_{max} \tag{8}$$

The initial search domain for locating facilities is all the available grid cells, unless the inclusion/exclusion areas constrain the location of facilities to certain grid cells. Facility locations are encoded by the grid cell numbers in GA. The search domain of the facility orientation is 0 and 90, which is encoded by binary numbers. The search domain of the facility size is determined by the planner through predefining the possible sizes of facilities, and is encoded by the ordinal number (i.e., 1, 2, 3, etc.) assigned to each predefined size. From this search domain, GA randomly creates layouts and examines the satisfaction of the hard constraints. If all the constraints are satisfied, the created site is feasible. Otherwise, a new layout should be generated. The feasibility of the site should also be examined after crossover and mutation operations. The construction plan variables and their search domain (i.e., possible values) are also predefined by the planner based on their constraints. For instance, the search domain of the number of material handlers can be defined as an ordinal number from 2 to 5 based on the site congestion and financial constraints.

When feasible candidate solutions are produced in GA, the project costs as their fitness function are measured by the cost evaluation module as described in the next subsection.

Cost evaluation module

In the cost evaluation module, simulation is employed to mimic the construction process, and estimate the total cost of the project by capturing the impacts of site layout and construction plan variables on project costs. The main elements of the simulation model are construction operation tasks, on-site transportation tasks, the required resources for performing the tasks, and the facility location and size. The location of facilities directly affects the duration of on-site transportation tasks, and can indirectly delay some construction operation tasks that are dependent on the on-site transportation tasks. The facility size, which specifies the space resource for some tasks (e.g., offloading materials into a facility), can delay those tasks if the facility does not have enough available space. The managerial actions to remedy space shortage can also be modeled, and the impact of facility size on the project cost can be quantified through simulation. It should be emphasized that some construction plan decisions such as the material delivery plan can influence the cost efficiency of facility size (see RazaviAlavi and AbouRizk (2015) for further information). This influence is also quantifies by simulation. To build the simulation model and estimate the cost, other data, such as the task durations, dependency between tasks, and cost data, are the inputs. In addition, uncertainties inherent in construction projects can be considered in the simulation model using probabilistic input data. The total project cost comprises of construction costs and site layout costs, and is calculated using the following equation:

$$\text{Total Cost} = \text{Construction Costs} + \text{Site Layout Costs} \tag{9}$$

Simulation is used to estimate the construction costs, the site layout costs, and ultimately the total cost for all the feasible chromosomes created by GA. Construction costs may include the direct and indirect costs of the project (e.g., labor and equipment costs), and managerial action costs, as required. The site layout costs can cover the costs for mobilization, maintenance and demobilization of facilities, which can depend on the size of the facilities. Running the simulation model for each chromosome, the total cost is estimated and returned to GA as the fitness value of the examined chromosome.

Integration of simulation and optimization modules

The last step in development of the framework is integration of GA and simulation, which continuously interact in order to find the near-optimum solution. Details of this integration are illustrated in Fig. 4. As seen in this figure, GA creates the first generation of the chromosomes, which must satisfy the hard constraints. Next, simulation estimates the total cost of the chromosomes as their fitness function. Then, crossover and mutation operations are performed on the chromosomes in order to produce a new generation of chromosomes. It should be emphasized that the created chromosomes for the new generation must also satisfy the hard constraints. Simulation evaluates the fitness function of the new chromosomes, with the process being iterated until the maximum number of generations is reached. The model is developed within Simphony (Hajjar and AbouRizk, 1996), Simphony.NET 4.0 version, which is a tool for building simulation models, and which has a programmable platform for developing new components. Hence, GA is developed within Simphony as a new component, and is integrated with the simulation model created using Simphony’s simulation components.

Case study

In this section, applicability of the framework is demonstrated in a steel erection project. The construction process of this project has been inspired from a real project in Fort McMurray, Alberta, Canada. The process involves in the delivery of three types of steel materials to the site, storing them on the site, handling the material from the storage to the structures, and erection of the materials. The preliminary plan for material delivery and steel erection is illustrated in Fig. 5 (a). The start date of the material delivery may be changed according to the planner, which will be discussed later. The materials are delivered to the site each day at the rate shown in Fig. 5(a). It is assumed that the risk of late delivery of the material is 20% for 1 day, and 10% for 2 days. In Fig. 5 (a), the sequence of erecting the material each day is indicated by the numbers on the bars. The process of steel erection, and the required resources to be modeled through simulation, are depicted in Fig. 5 (b). For material handling, a number of forklifts are deployed, which are shared among all types of materials. For erecting the materials, two cranes, namely Crane 1 and Crane 2, are deployed. However, Material 1 and Material 2 are erected using only Crane 1 and Crane 2, respectively, while Crane 1 is utilized for 50% of Material 3, and Crane 2 is utilized for the other 50%. For the materials sharing the same resources, the priority for capturing the crane is given first to the material with a lower sequence number. If the sequence numbers are equal, Material 3 will have a lower priority. One of the advantages of simulation recognized in this case study is that it can sophisticatedly model resources and their complex interactions.

As seen in Fig. 5 (b), if the on-site storages do not have enough space for the delivered materials, managerial action will dictate that they will be stored in the off-site storages. Then, when the space becomes available, they are transported to the site. Using the off-site storage incurs extra costs including time-dependent cost for renting the storage, and one-time cost for transportation, which are considered in the model. To avoid these costs, the planner may intend to allocate more space to the on-site storages, which induces extra costs for mobilization, maintenance and demobilization of the storage, and also may not be possible due to space limitations on the site. Otherwise, the planner can adopt a just-in-time delivery scheme for the materials, which may cause late delivery of the material due to the abovementioned risks in the material supply chain, and may expose the project to reduction of the production rate. Thus, the size of on-site storages, the cost of the off-site storage, availability of space on the site, the material delivery plan, risk of late delivery of the materials, and the project production rate are the dependent parameters that should be considered in decision making.

In addition to the storage size, the location of the on-site storages, which drives transportation time of the forklifts as material handlers, can have an impact on the project production rate. However, this impact can be mitigated by deploying more forklifts, which increases equipment costs. The location of the office and tool room influences the workers' travel time to reach the construction zone (i.e., offloading Area and Structure A and B), which ultimately impacts the production rate. Hence, the location of the on-site storages, office and tool room, the number of deployed forklifts, the cost of deploying forklifts, and the project production rate should be accounted for in decision making. Fig. 5 (c) shows dependency among the abovementioned factors, which are from different disciplines, using a causal loop diagram. In this diagram, independent variables are linked to dependent variables through arrows, while polarities of the arrows (i.e., positive or negative) shows how the changes of the independent variable affect the dependent variables (Sterman, 2000). This diagram confirms the significance of modeling facility size and location as well as construction operation and plan parameters in a unified simulation model. It also demonstrates how this framework addresses the drawbacks of the other methods, as discussed in the introduction section, by:

- modeling the impact of facility location on the production rate of the project,
- modeling construction plan variables such as the number of forklifts and the material delivery plan, and capturing their impacts on the efficiency of the site layout plan,
- modeling and quantifying the impact of facility size on the project costs, and

- optimizing the site layout and construction plan variables simultaneously.

The overview of the site layout with facilities that have predetermined locations is depicted in Fig. 6 (a). The variables considered in this study, including site layout variables and the construction plan variables, are presented in Tables 1 and 2, respectively. The search domain of the facility size and the construction plan variables are also presented in these tables. The total number of possible solutions for the construction variables is $3^4 \times 3^3$, and the total number of possible solutions for site layout variables considering one variable-orientation facility and assuming at least 10 possible locations for facilities is 2×10^6. This results in a high number of possible solutions (i.e., 4.374×10^9) for the problem, which further justifies the necessity of employing the presented framework to find the near-optimum solution. The hard constraints used for identifying the search domain for facilities' locations are presented in Table 3. The main inputs of the simulation model are given in Table 4.

The model is created in the Simphony environment using the discrete event simulation (DES) technique. GA's parameters used in the model are 75, 70, 0.9 and 0.1 for the number of generations, population size, crossover rate, and mutation rate, respectively. Having run the model, the near-optimum plans, encompassing the near-optimum site layout plan as illustrated in Fig. 6 (b), and the near-optimum construction operation plan as presented in Table 5, are identified with the total cost of $141,529.

To demonstrate the significance of integrating site layout planning with construction operation planning, the optimum plan is experimented with, using a single change to the construction operation plan: the number of forklifts is increased from 2 to 3. The result of the simulation model for this plan shows that the total cost is increased by 7%. This is because of the fact that adding one forklift to the resources did not significantly improve the production rate (because the material storages are close enough to the structures), while it increased the cost of deployed resources. Also, the changes in the construction plan variables can influence the efficiency of the layout. For instance, the optimum plan for delivery of Material 2 was Day 2 considering the second largest size for the storage of Material 2 as the optimum size. Assuming that delivery of Material 2 is decided as Day 4, the total cost is increased to $188,943. This assumption suggests a smaller material storage for Material 2 because less space may be required for storing materials. Having experimented this scenario using simulation, the total cost is reduced to $185,191, which is mainly because of the less costs for mobilization, maintenance and demobilization of the storage. This experiment verified that for such material delivery plan, the previous layout is no longer an optimum layout, and the smaller storage for Material 2 is more efficient. Consequently, ignoring the mutual impacts of site layout variables and construction operation variables may entail a suboptimum plan. It is noteworthy that the simulation model can provide the planner with more information, such as the project cost distribution (i.e., construction operation costs, extra storage costs, etc.), resource utilization, and the fullness of the storages, which are beyond of the scope of this paper.

Limitations of the framework

The presented framework was developed under the assumptions for facility size, orientation and location explained in the methodology section. In addition, the constraints considered in the framework were limited to the hard constraints for positioning facilities. The qualitative factors such as subjective closeness constraints between facilities that may exist in some layout planning problems were not accounted for in the framework. This is because of the fact that the subjective factors cannot be evaluated by the fitness function (i.e., total project cost), quantitatively defined in the framework.

Conclusion

In this study, a framework was developed to identify more cost-efficient site layouts and construction plans for projects, in a unified model. To this end, GA is employed as an optimization tool for generating feasible candidate solutions and heuristically searching for the near optimum variables, and is integrated with simulation, a suitable tool for modeling the construction processes and examining the cost-efficiency of candidate solutions. In GA, facility location constraints such as safety and environmental hazards, accessibility and planner's preferences are considered in the framework by modeling hard constraints. Simulation is used to properly quantify the impact of facility size and location on the project cost considering inherent uncertainties, resource interactions, and dynamics of the construction projects, which makes this framework superior to the existing methods. In addition, this study could comprehensively address the identified drawbacks of the most existing methods. Having implemented the framework in a case study successfully, its applicability in construction projects was substantiated. The main contributions of this study are summarized as follows:

- The mutual impacts of site layout and construction plans are thoroughly modeled in a unified simulation model, and their variables are simultaneously optimized in GA. This prevents suboptimum plans that result from attempting to optimize site layout and construction plans separately.
- Utilizing simulation to examine the goodness of the candidate solutions yields more realistic plans, since simulation can mimic the real world scenarios of construction projects, and can estimate efficiency of the plans by quantifying the impacts of facility size and location on the project cost, as well as modeling construction uncertainties, resource

interactions, and, particularly, the inter-dependencies between the site layout and construction plan variables.

In light of this study, developing dynamic SLP, in which the site layout variables may change over different phases of the project, can be investigated in future research.

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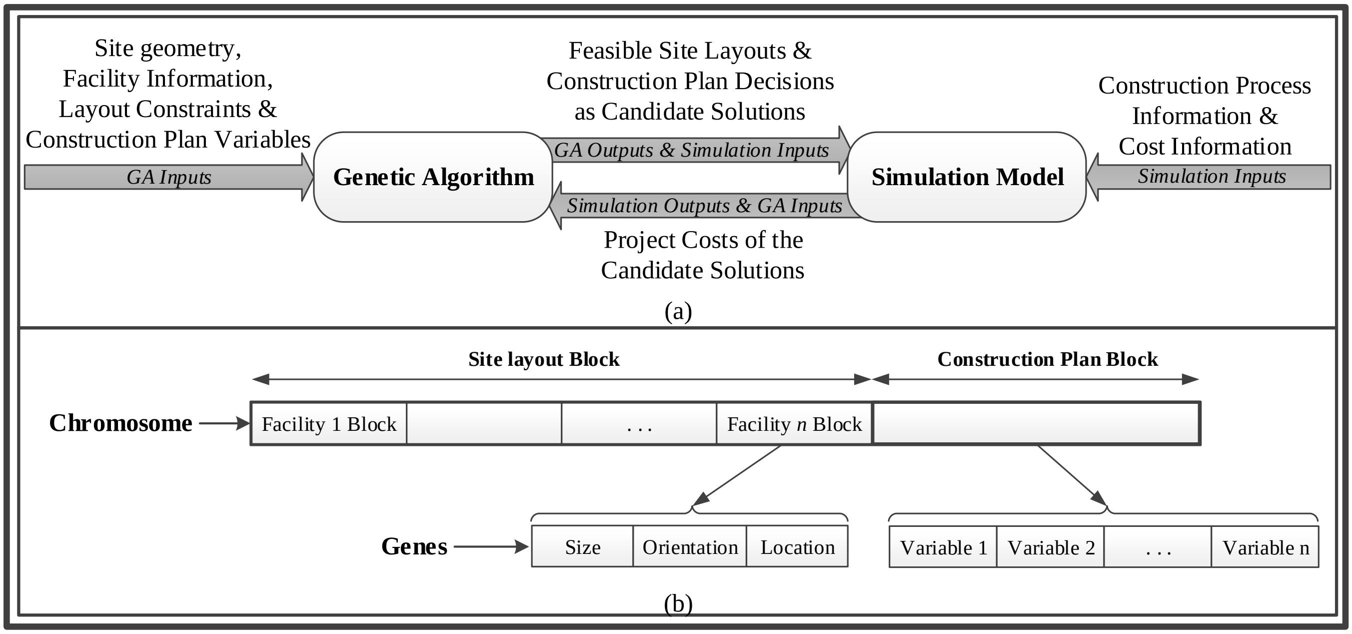
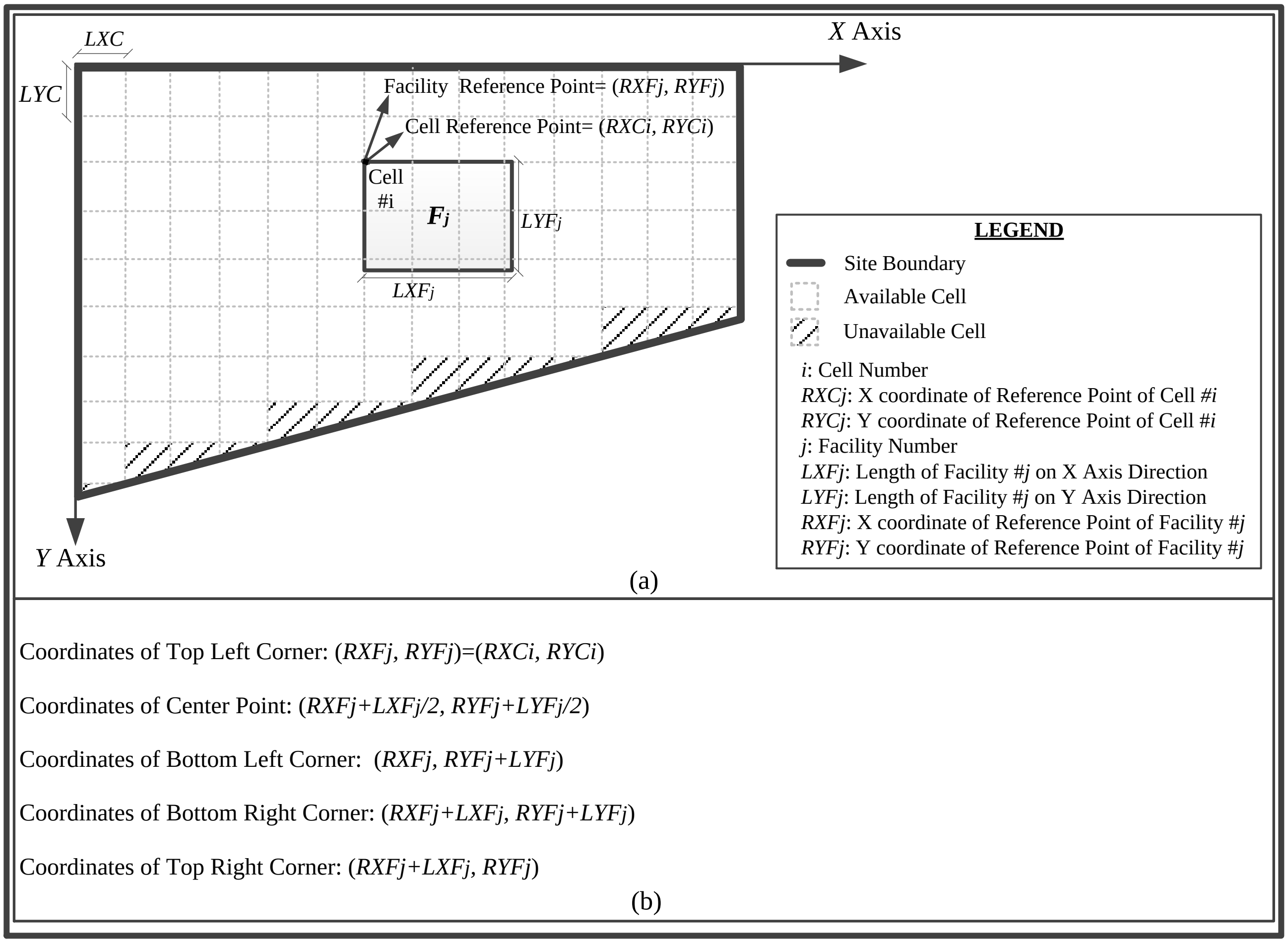


Fig. 1. (a): Integration of GA and simulation, and (b): Composition of the chromosome in GA



Coordinates of Top Left Corner: $(RXFj, RYFj)=(RXCi, RYCi)$

Coordinates of Center Point: $(RXFj+LXF_j/2, RYFj+LYF_j/2)$

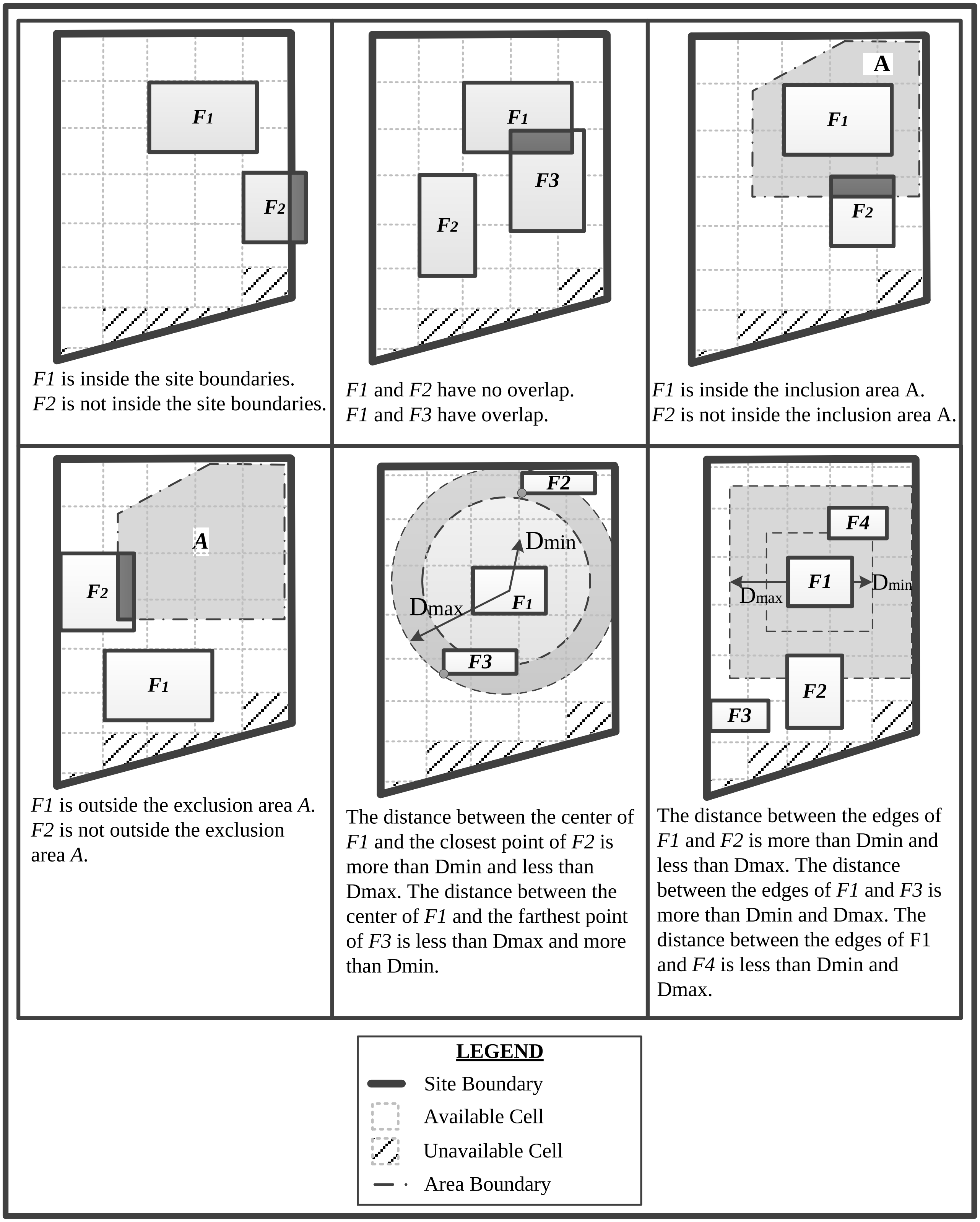
Coordinates of Bottom Left Corner: $(RXFj, RYFj+LYFj)$

Coordinates of Bottom Right Corner: $(RXFj+LXF_j, RYFj+LYF_j)$

Coordinates of Top Right Corner: $(RXFj+LXF_j, RYFj)$

(b)

Fig. 2. (a): Composition of the chromosome in GA, and (b) calculation of coordinates of facility points



F1 is inside the site boundaries.
F2 is not inside the site boundaries.

F1 and *F2* have no overlap.
F1 and *F3* have overlap.

F1 is inside the inclusion area A.
F2 is not inside the inclusion area A.

F1 is outside the exclusion area *A*.
F2 is not outside the exclusion area *A*.

The distance between the center of *F1* and the closest point of *F2* is more than Dmin and less than Dmax. The distance between the center of *F1* and the farthest point of *F3* is less than Dmax and more than Dmin.

The distance between the edges of *F1* and *F2* is more than Dmin and less than Dmax. The distance between the edges of *F1* and *F3* is more than Dmin and Dmax. The distance between the edges of F1 and *F4* is less than Dmin and Dmax.

Fig. 2. Site layout hard constraints

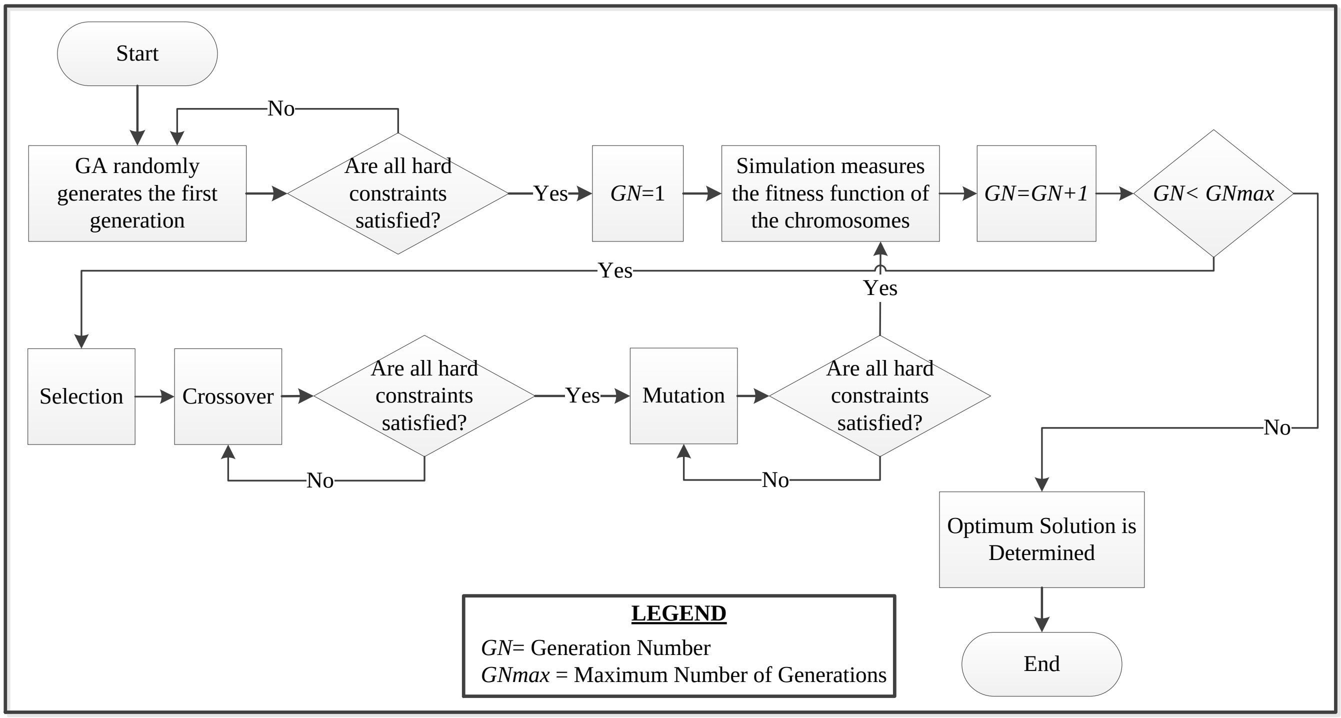


Fig. 3. Finding near-optimum solution through integration of GA and simulation

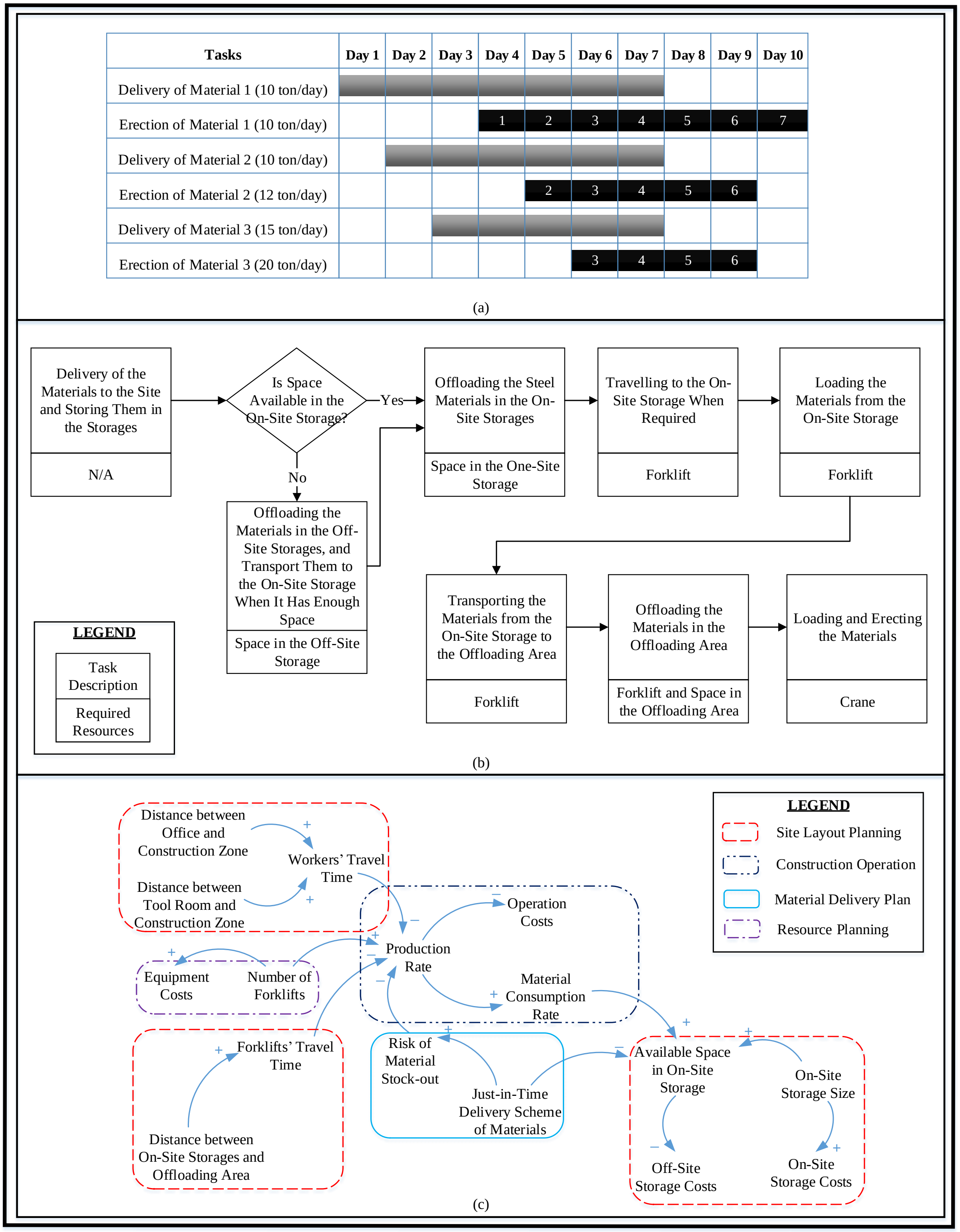
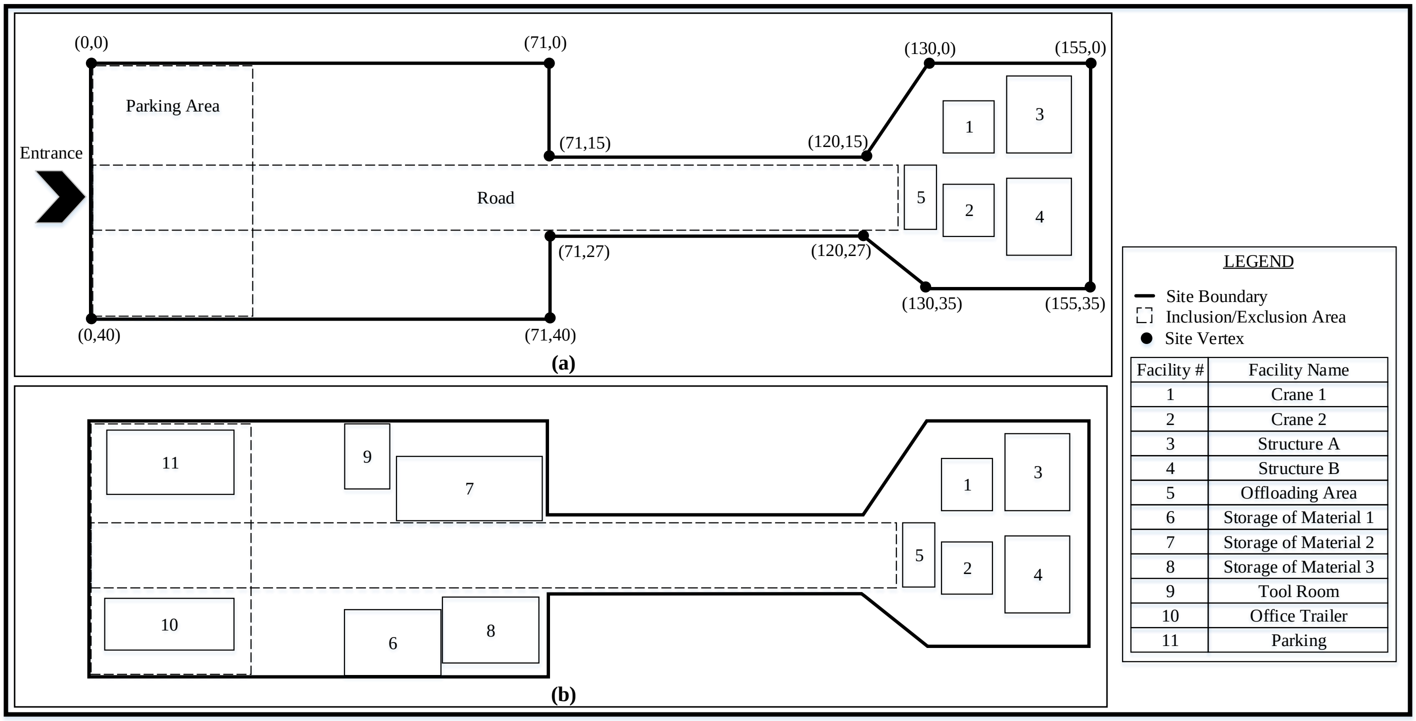


Fig. 5. (a): Material delivery planning, (b): Streel erection process, and (c): Dependency of variables



Facility #	Facility Name
1	Crane 1
2	Crane 2
3	Structure A
4	Structure B
5	Offloading Area
6	Storage of Material 1
7	Storage of Material 2
8	Storage of Material 3
9	Tool Room
10	Office Trailer
11	Parking

Fig. 6. (a): Overview of the site layout, and (b): Optimum site layout

Table 1. Site layout variables

Facility	Site Layout Variables			Possible Facility Size (Capacity)[a]
	Size	Location	Orientation	
Structure A				10m×12m
Structure B				10m×12m
Crane 1				8m×8m
Crane 2				8m×8m
Offloading Area				5m×10m (2 tons)
Office		×		20m×8m
Tool Room		×	×	10m×7m
Parking		×		20m×10m
Storage of Material 1	×	×		30m×10m (50 tons), 22.5m× 10m (40 tons) or 15m×10m (30 tons)
Storage of Material 2	×	×		30m×10m (50 tons), 22.5m× 10m (40 tons) or 15m×10m (30 tons)
Storage of Material 3	×	×		30m×10m (50 tons), 22.5m× 10m (40 tons) or 15m×10m (30 tons)

[a] Capacity is defined for the facilities that maintain steel materials

Table 2. Construction plan variables

Construction plan variables	Possible Values
The number of forklifts	1, 2 or 3
The starting date of Material 1 delivery	Day 1, Day 2 or Day 3
The starting date of Material 2 delivery	Day 2, Day 3 or Day 4
The starting date of Material 3 delivery	Day 3, Day 4 or Day 5

Table 3. Defined site layout hard constraints

Constraint description	Defined Constraints
The Parking must be close to the site entrance	Including Parking in the Parking Area for being close to the entrance
No facilities must block Road	Excluding all facilities from the Road Area for safety and accessibility
Office must be close to Parking	Maximum distance between centers of Office and Parking less than 30 m as a closeness constraint
Cranes must have access to Offloading Area	Maximum distance between center of cranes and farthest point of Offloading Area must be less than 20 m for accessibility of the cranes to the materials for loading them
Crane 1 must have access to the Structure A	Maximum distance between centers of Crane 1 and Structure A must be less than 20 m for accessibility of the crane to the structure for erection of the material
Crane 2 must have access to the Structure B	Maximum distance between centers of Crane 2 and Structure B must be less than 20 m accessibility of the crane to the structure for erection of the material
All facilities except for Offloading Area and Structure A and B must be out of the Cranes' zone	Minimum distance between the centers of the cranes and the closest point of all facilities except for Offloading Area and Structure must be greater than 20 m for safety
No facilities except for Cranes must be located in the construction zone around Structure A and B	Minimum distance between the edges of the structures and all facilities except for the cranes must be greater than 5 m for safety

Table 4. Simulation inputs

Input	Value
Forklift travel speed	Triangular a (3000, 3500, 4000) (m/hr)
Loading 1 ton of material from the storage by forklift	Uniform b (0.08, 0.12) hr
Offloading 1 ton of material in Offloading Area by forklift	Uniform (0.05, 0.1) hr
Loading 1 ton material from Offloading Area by the crane	Uniform (0.08, 0.15) hr
Erection of 1 ton of Material 1 by crane	Triangular (0.3, 0.4, 0.45) hr
Erection of 1 ton of Material 2 by crane	Triangular (0.2, 0.3, 0.35) hr
Erection of 1 ton of Material 3 by crane	Triangular (0.15, 0.2, 0.25) hr
Workers' travel speed	Uniform (2000, 2500) (m/hr)
Construction costs apart from forklift costs	$2100 /hr
Forklift costs	$130/hr
Mobilization, maintenance and demobilization of the storage with size 30m×10m	$8000
Mobilization, maintenance and demobilization of the storage with size 22.5m× 10m	$6000
Mobilization, maintenance and demobilization of the storage with size 15m×10m	4000
Transportation cost of materials to the off-site storage	$500 per material delivery
Off-site storage rent cost	$30 per ton of material per day

[a] Triangular (L, M, H) is the triangular probability distribution, where L, M and H are the lower bound, mode and higher bound, respectively.

[a] Uniform (L, H) is the uniform probability distribution, where L and H are the lower and higher bounds, respectively.

Table 5. Optimum facility size and construction plan variables

Facility size/construction plan variables	Optimum Value
Size of Storage of Material 1	15 m × 10 m
Size of Storage of Material 2	22.5 m × 10 m
Size of Storage of Material 3	15 m × 10 m
The number of forklifts	2
The starting date of Material 1 delivery	Day 1
The starting date of Material 2 delivery	Day 2
The starting date of Material 3 delivery	Day 4