Northumbria University
NEWCASTLE

Genetic Algorithm–Simulation Framework for Decision Making in Construction Site Layout Planning

SeyedReza RazaviAlavi, PhD Candidate <reza.razavi@ualberta.ca>
Hole School of Construction Engineering Department of Civil and Environmental Engineering
University of Alberta. 5-080 Markin CNRL Natural Resources Engineering Facility
Edmonton, Alberta, Canada T6G 2W2
*Corresponding Author: Simaan AbouRizk, PhD, PEng, Professor <abourizk@ualberta.ca>
Hole School of Construction Engineering Department of Civil and Environmental Engineering
University of Alberta. 5-080 Markin CNRL Natural Resources Engineering Facility
Edmonton, Alberta, Canada T6G 2W2

Abstract

Site layout planning is a complicated task in many construction projects due to the diversity of decision variables, conflicting objectives, and the variety of possible solutions. This paper describes a framework that facilitates decision making on site layout planning problems. The framework consists of three phases: 1) Functionality Evaluation Phase (FEP), which qualitatively evaluates using a new method, 2) Cost Evaluation Phase (CEP), which quantitatively evaluates the goodness of the layouts using simulation, and 3) Value Evaluation Phase (VEP), which selects the most desirable layout from both qualitative and quantitative aspects. This framework also takes advantage of heuristic optimization through Genetic Algorithm (GA) to search for the most qualified layouts within FEP. The main contribution of this research is to introduce a novel method for evaluating quality of layouts, which more realistically model the closeness constraints, and consider size and location desirability in the evaluating function. Also, using simulation for estimating project cost improves the effectiveness of the framework in practice, since simulation can model construction processes, uncertainties, resources and dynamic interactions between various parameters. Applicability of the framework is demonstrated through a case study of the layout planning of a tunneling project.

Keywords*: Site layout planning, optimization, genetic algorithm, simulation*

Introduction

Site layout planning (SLP), the process of identifying the size and location of temporary facilities, is a challenging problem in many construction projects. In practice, there are several site layout alternatives, and a decision making tool could aid in selecting the most efficient site layout. Different types of constraints are considered in SLP which may not be entirely satisfied in any of the alternatives. Thus, properly evaluating and comparing the different aspects of site layout alternatives is essential in decision making.

SLP has been widely studied in the literature. The majority of past research focused on finding the optimum location for facilities (e.g., Sadeghpour, et al. (2006) and Zhang and Wang (2008)). In past research, different constraints that are affected by the location of facilities, such as on-site transportation costs, safety, accessibility, and planners' preferences, have been considered. Conventionally, the sum of weighted distance function (SWDF) has been utilized to evaluate the desirability of layouts, which is defined as $\sum w \times d$, where w reflects the weight of interactions or closeness factors between facilities, and d represents the distance between facilities (Rosenblatt 1986). Different approaches exist for defining w: 1) quantitative approaches (e.g., Zhang and Wang (2008)), that only consider the transportation cost and define w as the transportation cost per unit of distance based on the frequency and means of transportation between facilities, and 2) qualitative approaches (e.g., Elbeltagi, et al. (2004)), in which w is the closeness weight between facilities that can reflect the transportation cost, safety and environmental hazards, and/or any other closeness constraints between facilities

Since examining all possible solutions is not feasible, heuristic optimization methods such as genetic algorithm (Osman, et al., 2003), ant colony (Ning, et al., 2010), particle swarm (Zhang and Wang, 2008), and particle bee (Lien and Cheng, 2012) have been employed to optimize SWDF.

Despite the simplicity of using SWDF, it has the following limitations and drawbacks:

- The efficiency of SWDF in practice is in question. The weights considered in SWDF can reflect the impact of facility locations on the on-site transportation cost, but cannot quantify their impacts on the entire project. For instance, a long distance between two facilities not only entails more material transportation costs between them, but also may result in late delivery of the material, which can interrupt the workflow and cause idleness of the resources demanding the material for production. This will further lead to loss of production rate and costs. These impacts depend not only on the transportation distance but also on the number of material handlers, their speed, and the production cycle time of the resources. In addition, construction projects contain dynamic processes with inherent uncertainties such as variation in production rate and duration of the activities. The inability of SWDF to model these factors, and quantify the consequences of the on-site transportation on the project, can result in planning inefficient layouts; this was substantiated by Alanjari, et al. (2014).
- SWDF only considers the locations of the facilities as a variable, and overlooks size of the facilities as another factor that can significantly impact the productivity and cost of projects. On construction sites, the size of some facilities which predominantly maintain materials (e.g. material storages), is variable and should be determined through a site layout planning process. The size of such facilities can influence the material flow and project costs (RazaviAlavi and AbouRizk, 2015). For instance, insufficient size of material storage on the site may entail extra costs for changing the material delivery plan, or storing materials off the site and transporting them to the site when space is available. Facility size is more critical on congested sites, in which the planner may not be able to provide sufficient size for all facilities, and has to shrink the size of some facilities or position them in unfavorable areas. In addition, allocating a facility more space than required may incurs

extra costs for mobilization, maintenance, and demobilization of the facility (See RazaviAlavi and AbouRizk (2015) for further information on the impact of facility size on construction projects). Hence, neglecting facility size as a variable in SWDF can cause inefficiency of the layout.

- In SWDF, satisfaction of constraints is a linear function of distance, which means by increasing or decreasing (depending on the type of the constraint) the distance between two facilities, the constraint between those facilities are satisfied more without any limits. This may not be realistic for all constraints since the nature of some constraints could be different. For instance, for the safety hazard of falling objects from a crane, the degree of the hazard after a certain distance between facilities is zero. Hence, using SWDF entails a flaw in evaluating the objective function because positioning these facilities unnecessarily far from each other can compromise the location of two other facilities that should have been positioned closer to each other. That is, the efficiency of SWDF can be improved by defining different functions that more realistically model different types of distance constraints.

This study aims to address these drawbacks by developing a framework enabling planners to assess site layout plans using different aspects (including adjacency preferences, safety, accessibility, and facility size), more realistically model the impact of site layout on the project costs, and decide on the most desirable plan.

Decision Making Framework

The proposed framework for decision making on SLP consists of three phases: 1) Functionality Evaluation Phase (FEP), 2) Cost Evaluation Phase (CEP), and 3) Value Evaluation Phase (VEP). The overview of the framework is depicted in Figure 1. In the FEP, the site geometry and facility information including the type, shape and size of the facilities, as well as hard and soft constraints (which are discussed in detail later) are the inputs of the heuristic optimization. The reason for using heuristic optimization is that there are a large number of possible solutions in SLP. In this study, genetic algorithm (GA) is adopted as an optimization method to heuristically search for the near-optimum layouts evaluated by the predefined fitness function. GA's fitness function is the Functionality Index (FI) that addresses the satisfaction level of different constraints including distance constraints, facility size, and favorable/unfavorable areas for positioning facilities. Using GA, a set of elite layouts, which are feasible (i.e., completely satisfy hard constraints) and qualified (i.e., satisfy soft constraints to the highest levels), are identified and imported to CEP. In CEP, the cost of the elite layout is evaluated using simulation. Simulation is a suitable tool for mimicking construction processes and quantitatively measuring important parameters such as project time, cost and productivity. Application of simulation is more effective in modeling projects with uncertainties, technical or methodical complexity, and repetitive tasks (AbouRizk, 2010), which are common in most construction projects. Simulation has been successfully applied in quantifying the impact of facility locations on transportation time (e.g., Tommelein (1999), and Azadivar and Wang (2000)) and the impact of facility size on the project cost (RazaviAlavi and AbouRizk, 2015). Modeling resource interactions (Alanjari, et al., 2014) and providing the planners with more information such as total time in system and resource utilization (Smutkupt and Wimonkasame, 2009) were recognized as the prominent advantages of using simulation in SLP.

In CEP, the elite layouts, along with the construction process information and the cost information, are used to build the simulation model. Simulation evaluates the Cost Index (CI) of all elite layouts. Then, in VEP, the total value of the elite layouts is assessed using the Value Index (VI) defined as a ratio of FI to CI. Comparing VI of the layouts, the most desirable layout can be selected. The details of this framework are described in the following subsections.

Functionality Evaluation Phase (FEP)

The FEP phase aims to produce feasible layouts and heuristically find the most qualified ones. The inputs, procedures and assumptions of this phase are as follows.

Site geometry

The geometry of the site should be specified to identify the places that facilities can be placed. In this study, any polygon shape can be considered as the site boundaries by identifying coordinates of the polygon's vertices. To reduce the searching space for positioning facilities, underlying gridlines are adopted. Gridlines create cells on which facilities can be positioned. The size of the cells depends on the size of the site and facilities, and the accuracy that the planner seeks. The common suggestion for the cell size is the smallest dimension of the facilities.

Facility information

This information comprises the attributes of the facilities that should be determined as inputs, such as the type, shape and size of each facility. Different types of facilities can be identified: a) predetermined or movable location, b) predetermined or variable orientation, and c) predetermined or variable size. Any attribute (i.e., location, orientation, and size) of a facility that is variable will be determined through GA optimization. In this study, the shape of the facilities is limited to rectangles, and the orientation is limited to 0 and 90 degrees. Considering these assumptions, the size of the facilities is specified by their length and width.

Hard constraints

Hard constraints are the ones that must be satisfied. Any layout that does not satisfy the hard constraints is considered unfeasible. The GA optimization checks satisfaction of all hard constraints to prevent producing unfeasible layouts. The following hard constraints are considered in this study:

- Being inside the boundaries: All the facilities must be positioned inside the site boundaries.
- Non-overlapping: No facilities can be overlapped.
- Inclusion/exclusion area: Given facilities must be positioned inside/outside the boundaries of an area identified by coordinates of its vertices.
- Minimum/maximum distance ($D_{min/max}$) between facilities: Two facilities must have a minimum or maximum distance measured between the selected points of two facilities. Points can be centers, edges, closest points and/or farthest points of facilities, as depicted in Figure 2(a).

The assumption for positioning facilities is that the top left corner of the facility is positioned at the top left corner of the designated cell. The cells and facilities are numbered to specify which cell is designated to which facility. The top left corner of the cells and facilities are considered their reference points, and the Cartesian coordinate system is used to formulate the position of the facility as shown in Figure 2(b).

Given the fact that the coordinates of the cell corners can be calculated using the coordinates of the site vertices and the cell size, the coordinates of the reference point and the center point of the facilities are calculated as follows (once Cell #i is designated to Facility #j (F_j)):

Reference point coordinates: $(RXF_j, RYF_j) = (RXC_i, RYC_i)$ (1)

Center point coordinates: $(CXF_j, CYF_j) = (RXF_j + LXF_j/2, RYF_j + LYF_j/2)$ (2)

To formulate satisfaction of the hard constraints, the following formulas are considered:

- 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:

$$RXF_{Xmin} + LXF_{Xmin} \leq RXF_{Xmax}; \text{ OR} \quad (3)$$

$$RXF_{Ymin} + LXF_{Ymin} \leq RXF_{Ymax} \quad (4)$$

where 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 RXF of two facilities are equal, the second equation must be satisfied, and if RYF 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.
- For minimum or maximum distance constraint ($D_{min/max}$) between two points of Facility #j and #k, Euclidean method is used for measurement, and the corresponding equation should be satisfied:

$$\text{For the minimum distance constraint: } D_{min} \leq \sqrt{(x_j - x_k)^2 + (y_j - y_k)^2} \quad (5)$$

$$\text{For the maximum distance constraint: } D_{max} \geq \sqrt{(x_j - x_k)^2 + (y_j - y_k)^2} \quad (6)$$

  - where $a = (x_j, y_j)$ and $b = (x_k, y_k)$ are the specified points of facility #j and #k, respectively, for measuring the distance (see Figure 2(a)).
- For the minimum distance constraint (D_{min}) between edges of Facility #j and #k, satisfying either:

$$|CXF_j - CXF_k| - (LXF_j + LXF_k)/2 \geq D_{min} \quad (7)$$

or (8)

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

- For the maximum distance constraints (D_{max}) between edges of Facility #j and #k, satisfying both:

$$|CXF_j - CXF_k| - (LXF_j + LXF_k)/2 \leq D_{max} \quad \text{and} \quad (9)$$

$$|CYF_j - CYF_k| - (LYF_j + LYF_k)/2 \leq D_{max} \quad (10)$$

Soft constraints

Soft constraints are those that may be dissatisfied or be satisfied to only a certain extent. Each constraint is assigned a weight (W) that specifies the importance of satisfying it. Satisfying the soft constraint has different forms depending on the type of the constraint. Three types of constraints are considered in this study: 1) distance constraints, 2) size constraints and 3) inclusion/exclusion constraints. The level of satisfaction of the constraints is measured by the Functionality Index (FI) using the following equation:

$$\mathrm{FI} = \frac{\sum \mathrm{W_{ij}} \times \mathrm{ds_{ij}} + \sum \mathrm{W_k} \times \mathrm{Ss_k} + \sum \mathrm{W_l} \times \mathrm{I/Es_l}}{\sum \mathrm{W_{ij}} + \sum \mathrm{W_k} + \sum \mathrm{W_l}} \tag{11}$$

where, W_{ij} is the weight assigned to the distance constraint between facilities i and j ($i \neq j$), ds_{ij} is the distance constraint satisfaction between facility i and j, W_k is the weight assigned to the size constraint of facility k, Ss_k is the size constraint satisfaction of the facility k, W_l is the weight assigned to the inclusion/exclusion soft constraint of facility l, and I/Es_l is the inclusion/exclusion constraint satisfaction of facility l.

W_{ij}, W_k and W_l are assigned a number between 1 (lowest level of importance) and 10 (highest level of importance). The method for calculation of ds, Ss and I/Es is described as follows:

Distance constraint satisfaction (ds)

ds, which varies between 0 and 1, is a function of distance between two facilities measured from the edges or the selected points using the Euclidean method. For the closeness constraints that intend to position two facilities close to each other, the level of satisfaction is reduced by increasing the distance. On the other hand, for the closeness or safety constraints that intend to position two facilities far from each other, the level of satisfaction is increased by increasing the distance. However, as discussed earlier, the form of satisfaction varies due to the different nature of each constraint. For example, as seen in Figure 3 (a), once it is desirable to position two facilities close to each other, within a certain distance (d_1), the constraint can be completely satisfied. Farther than d_1, the level of satisfaction can be reduced by increasing the distance until it reaches d_2. Distance farther than d_2 does not satisfy that constraint. Figure 3 (b) illustrates the example of a distance constraint to prevent falling objects from a crane on a facility. If the facility is positioned farther than the distance of d_3, the constraint is completely satisfied. Otherwise, its level of satisfaction is zero. In general, assuming that ds varies linearly by d, the form of ds can be identified by determining the coordinates of the points connected to each other consecutively. Given the fact that there is no limitation for the number of the points, most forms can be defined by three points (i.e., P_1, P_2 and P_3), as shown in Figure 3 (c). Those points are also illustrated in Figure 3 (a) and (b). The coordinates of the points (i.e., P_x and P_y) represent d and ds, respectively. It should be noted that P_x must be 0 for the first point. For a given d as a distance measured between two facilities, the distance satisfaction ds can be calculated using the following equation:

$$\mathrm{ds} = \begin{cases} \dfrac{\mathrm{ds}_2 - \mathrm{ds}_1}{\mathrm{d}_2} \times \mathrm{d} + \mathrm{ds}_1 & \text{if } 0 \leq \mathrm{d} \leq \mathrm{d}_2 \\ \dfrac{\mathrm{ds}_3 - \mathrm{ds}_2}{\mathrm{d}_3 - \mathrm{d}_2} \times \mathrm{d} + \mathrm{ds}_3 - \dfrac{\mathrm{ds}_3 - \mathrm{ds}_2}{\mathrm{d}_3 - \mathrm{d}_2} \times \mathrm{d}_3 & \text{if } \mathrm{d}_2 < \mathrm{d} < \mathrm{d}_3 \\ \mathrm{ds}_3 & \text{if } \mathrm{d} \geq \mathrm{d}_3 \end{cases} \tag{12}$$

In the case that d_1=d_2 or d_2=d_3, where two values exist for ds for a single d (e.g., Figure 3 (b)), the highest value is considered an assumption for ds.

Size constraint satisfaction (Ss)

Considering the location constraints and limited space on congested sites, it may not be possible to allocate the desirable sizes to all facilities on some sites. As a result, the planner may select smaller sizes for some facilities, which is less desirable. To measure the size constraint satisfaction, first, a weight (W) is assigned to the importance of the constraint for a specific facility. Then, the planner determines different sizes for that facility and assigns Ss, which can have a value between

0 and 1. For example, if the planner defines three sizes for a facility and assigns 10 to the weight, and 0.2, 0.5, and 1 as Ss to each size, respectively, when the second size was selected in the layout, the total size satisfaction (W×Ss) equals 5 (10×0.5).

Inclusion/exclusion soft constraint satisfaction (I/Es)

This soft constraint addresses the preferences to position facilities inside/outside areas specified by the planner. Similar criteria can be defined as a hard constraint. The only difference is that the hard constraints must be satisfied while the soft constraints may be dissatisfied. That is, the planner identifies a favorable area (inclusion area) or an unfavorable area (exclusion area) for positioning a facility as a soft constraint, and assigns a weight (W) to it to specify the importance of satisfying the constraint. If the facility is positioned inside the inclusion area, or outside the exclusion area, the level of satisfaction (I/Es) equals 1. Otherwise, it equals zero.

Genetic Algorithm (GA)

GA is a heuristic optimization method based on biology used to search for near-optimum solutions. The site geometry, facility information, hard constraints and soft constraints are the inputs of GA. The first step in GA is to identify the variables and their searching space. Location, orientation and size are three attributes of the facilities to be optimized through GA. In GA, "genes" represent optimizing variables. A set of genes, namely a "chromosome," composes one candidate solution. The composition of the chromosomes is shown in Figure 4 (a). As seen in this figure, the chromosome is conceptually divided into blocks of genes where each block is related to a facility, and n is the total number of facilities. Each block can have at most three genes allocated to location, orientation and size of that facility if they are variable. If they are not variable, the corresponding genes are eliminated. The searching domain for the location of the facilities is identified using the site geometry information and site hard constraints encoded by the cell number designated to the facility. The searching domain for the orientation of facilities is 0 and 90 degree encoded by a binary number. For the size, the searching domain depends on the number of sizes defined by the planner for that facility encoded by the ordinal number (i.e., 1, 2, 3, etc.) assigned to each predefined size. Once the genes and their searching domains are specified using the input data, GA optimization is initiated following the steps shown in Figure 4b to maximize FI as a fitness function. In this process, three operations (i.e., selection, crossover, and mutation) are performed on the chromosomes to evolve from one generation to the next. In selection, two chromosomes are randomly selected for crossover while the fitter chromosomes (i.e., chromosomes with higher FI) have a higher chance of being selected. In crossover, some genes of the selected chromosomes are randomly swapped. For mutation, one or more genes are randomly selected and its value is altered to another value from its searching domain (see Mitchell (1999) for further information on GA operations).

The feasibility of the created chromosomes is also checked after crossover, mutation, and randomly generating the first generation. That is, all chromosomes (i.e., layouts) must satisfy the hard constraints. Performing these operations results in creating a new generation, and this process is iterated to reach the maximum number of generations. The population size (the number of chromosomes in each generation), the crossover and mutation rates (the probability of performing crossover and mutation on the selected chromosomes), and the maximum number of generations are the GA parameters that should be determined by the user. In most past studies, GA aims to find a single near-optimum solution. However, in this study, GA identifies a set of near-optimum solutions as elite layouts due to the fact that the optimum layout from the qualitative aspects is not necessarily the most cost efficient layout in practice. To this end, all the site layouts generated through GA are stored in a repository and ranked based on their FI values. At the end of optimization, the planner can choose N number of the top ranked site layouts to be examined by simulation and forecast their cost efficiency. In fact, GA eliminates less qualified site layouts, which do not merit examination by simulation since running the simulation model for a large number of scenarios is costly and time consuming. Number N could be different in each problem depending on the variability of FI, sophistication of the simulation model for running different scenarios, and users' preferences. The recognized elite layouts are imported to CEP to evaluate their cost index, which is described in the next section.

Cost Evaluation Phase (CEP)

In CEP, simulation quantifies the project cost by capturing the impact of the site layout on the costs. Location of facilities can impact the on-site transportation including material, equipment and worker transportation, which can be modeled by simulation. Simulation can also model other construction operations, and quantify the impact of on-site transportation on them. The size of the facilities that contain material can also impact the project cost by interrupting the material flow when they are full, and/or taking managerial actions (e.g., use of off-site material storage) necessary to resolve space shortage. This impact can also be quantified by simulation (RazaviAlavi and AbouRizk, 2015). In general, the total project costs comprising the direct costs (e.g., crew, equipment and material costs), the indirect costs, and the site layout costs (e.g., mobilization, maintenance, and demobilization costs of the facilities) is considered in the simulation model.

To build the simulation model, the elite layouts, the construction process information and the cost information are the inputs. The construction process information includes the information on construction activities (e.g., the durations, required resources and sequences of activities) and the construction planning decisions influencing the efficiency of the site layout (e.g., material delivery and logistic plans). For instance, in order to model material flow, diverse variables such as construction production rate, facility size, distances between facilities, availability of the material handler resources, material delivery and/or removal plans, and the managerial actions to resolve space shortage may require modeling. That is, simulation can model existing dynamic and complex interactions between these parameters. Stochastic simulation can also suitably model uncertainties inherent in construction projects. To calculate CI of each layout, the total cost of the project for that layout is divided by the maximum cost of the project among all elite layouts.

Value Evaluation Phase (VEP)

Having examined FI and CI of the elite layouts, the total value of the layouts is evaluated in VEP using Value Index (VI). VI is defined as the following equation:

$$\text{Value Index (VI)} = \frac{\text{FI}}{\text{CI}} \tag{13}$$

As a result, the layout with the highest VI is identified as the most desirable layout since it has higher functionality with lower costs.

Overall, the proposed framework can address the drawbacks of SWDF, as discussed in the introduction section, by:

- modeling construction processes along with resources, uncertainties and dynamic interaction between different parameters, and quantifying the impact of facility location and size on the project using simulation in CEP,
- considering facility size in the framework using Ss in calculating FI, which qualitatively models facility size preferences, and using simulation to quantitatively model the facility size impacts on the project costs, and
- developing a new method (i.e., ds) to more realistically model closeness constraints

In the next section, the application of the framework is presented in a tunneling project.

Case Study

This case study was inspired by a real-world tunneling project executed by a Tunnel Boring Machine (TBM) in downtown Edmonton, Alberta, Canada. In the downtown area of the city, space availability is often a critical issue for construction projects, as it may not be possible to provide suitable space for all facilities, or locate them in suitable locations. In TBM tunneling projects, the distance between the shaft and spoil pile as well as the shaft and segment storage can affect the production rate (i.e., TBM excavation rate) by influencing the transportation time of soil and segments on the site. Long transportation time for soil and segments may entail idleness of the resources and reduction of the production rate. Also, the size of the spoil pile and segment storage can affect the project time and cost, since fullness of the spoil pile results in a halt to TBM excavation, and fullness of segment storage may incur extra costs to store segments off the site. Different factors can influence the project costs such as size and location of the spoil pile and segment storage, and construction planning variables such as the capacity of deployed trucks to remove the excavated soil from the site and the segment delivery plan to the site (see RazaviAlavi and AbouRizk (2014) for further information). Figure 5 (a), which uses a causal loop diagram to show dependencies among influencing factors, illustrates how the abovementioned variables can impact the total costs of the project. The impacts of these variables can be quantified by simulation in CEP, which is considered an advantage of this framework since FI cannot solely account for these factors. The repetitive nature of tunneling activities, uncertainties inherent in tunneling projects (e.g., geotechnical parameters of the soil, duration of activities and TBM breakdown) and the dynamic interactions between resources (e.g., TBM, train transporting materials inside the tunnel, and crane) also make simulation a suitable tool to model the tunneling process.

Table 1 lists the required facilities, their type and size. It illustrates that the segment storage and spoil pile are variable-size (and the planner has defined different sizes that could be assigned to them), while the other facilities have predetermined sizes. W and Ss for variable-size facilities are also given in Table 1. Since the planner would generally prefer to have larger storages on the site, higher Ss was assigned to the larger sizes. However, this preference could be compromised due to existence of other constraints, or high costs of having larger storage areas. The ability to consider variable facility size is another advantage of this framework over SWDF. Table 2 to Table 5 give the constraints defined for locating and sizing these facilities. It should be noted that some facilities (e.g., ventilation system, switch gear, construction box, and propane tank) are required on tunneling sites; however, their location and size do not have any impacts on the project cost, and their locations are constrained by the closeness constraints. That is, changes in the location of these facilities do not have any impacts on CI, and can only be evaluated by FI. For example, the distance between the propane tank and the site trailer does not impact CI. In this example, ds between propane tank's center and the closest point of the site trailer was defined with three points: (0,1), (1,1) and (5,0), because of the fact that the propane tank should be connected to the trailer for its use. Therefore, the distance farther than 5 m is not desirable, and the satisfaction for the distance more than 5 meters is considered 0. SWDF cannot appropriately model this kind of constraints because its objective function linearly varies by distance. That is, FI can more realistically evaluate distance constraints than SWDF. In addition, inclusion/exclusion area soft constraints can be considered in FI. For instance, the preference of the planner is to locate the spoil pile in the specified loading area due to the fact that trucks can access to the spoil pile from Access Road 1 more easily than Access Road 2, which interfaces South Gate Area. This preference was not a hard constraint for the planner, so it was modeled using the inclusion area soft constraint, which cannot be modeled by SWDF.

Figure 5 (b) depicts the site boundaries, the coordinates of the site vertices, and the specified inclusion/exclusion areas. The simulation model was built in the Simphony environment (Hajjar, and AbouRizk, 1996) using the discrete event simulation technique based on the information of a real project and some assumptions. The costs considered in the model included: 1) costs of crew and equipment such as crane, TBM, loader and truck measured with the unit of $ per hr, 2) Material supply costs such as a segment delivery costs measure, with the unit of $ per material delivered, 3) indirect costs such as engineering services with the unit of $, which was calculated as a percentage of the direct cost, 4) mobilization, demobilization and maintenance costs of the segment storage and spoil pile, which are variable-size facilities, measured with the unit of $ for each size, 5) costs for storing segments off site if segment storage were full, including the time-dependant costs for renting off-site storage measured with the unit of $ per day for each segment, and handling costs for transporting segments from off-site storage to the site, measured with the unit of $ per each handling for each segment.

The preliminary construction planning decisions assumed in this study as Scenario #1 are: deploying a truck with a capacity of 5 m^3 for removing the soil from the site, and a segment delivery plan of 48 segments/week to the site. To demonstrate variation of the layouts' efficiency by changing these variables, two more scenarios are also considered: Scenario #2, in which a truck with a capacity of 6 m^3 is deployed, and Scenario #3, in which the segment delivery plan is 48 segments per 8 days. Scenario #2 can reduce the delays caused by lack of space in the soil pile and improve the production rate, but incurs extra costs for deploying a larger truck. Scenario #3 can reduce the cost of off-site storage by delivering segments less frequently to the site, but can increase the risk of segment stock-out, since uncertainties of late segment delivery for 1 to 2 days were considered as 10% in the model. The impact of these changes on the project cost are evaluated through simulation. GA parameters used in the model are 100, 200, 0.9, and 0.04 for population size, number of generations, crossover rate and mutation rate, respectively. Having run GA optimization in FEP, 35 layouts were selected as elite layouts to be imported into the simulation model, condensing the significance of the differences between the FI values. The simulation model was run 100 times for each elite layout in CEP. The optimum layout was the one shown in Figure 5 (c) under Scenario #1 for construction planning decision. Note that the maximum cost from the three scenarios is considered when calculating CI.

Result Analysis

In this case study, GA produced different layouts of which FI varies from 0.36 to 0.88 with the average of 0.67. In CEP, only 35 layouts that could satisfy more than 85% of the soft constraints (i.e., FI>0.85) were selected as elite layouts. The list of elite layouts with their FI, CI and VI values as well as the size of the spoil pile and segment storage, and their distance from the shaft are presented in Table 6. As seen in this table, the layout with the highest functionality does not have the lowest cost. The optimum layout is Layout #1 under Scenario #1, which has the highest FI but 1.1% more costs than the least costs of the elite layouts. It is also seen that FI values of some layouts are the same, which is because the soft constraint satisfaction is not affected by changing the orientation of facilities from 0 to 90 degrees, or vice versa. Another reason is likely the soft constraints of inclusion/exclusion areas, which is satisfied by positioning a facility on any location inside/outside of the specified area. That is, several locations for a facility result in the same satisfaction value. This may also happen to some forms of the distance constraint satisfaction such as the ones shown in Figure 3 (a) and (b), which result in the same distance satisfaction value if the distance between the facilities is less than d_1 and d_3, respectively. This can bring about a more realistic model since in real projects, slight changes in location and/or orientation of some facilities may have insignificant impacts on the quality of the layout.

In Table 6, CI varies from 0.93 to 1, which shows that the project costs can vary significantly (i.e., about 7%) by changing the layout and construction planning variables. It is seen that the value of CI for some layouts are identical. As explained earlier, this is because the changes in the location of some facilities do not have any impacts on the project cost. Various comparisons and analyses can be undertaken using the presented data that demonstrate the capabilities of the framework. The following describes some of these analyses.

- Layout #1 as the optimum layout can be analyzed among the three construction planning scenarios. While using the larger truck could improve the production rate by reducing the probability of lacking space in the spoil pile and save some cost, the cost incurred by deploying the larger truck could balance this cost. So thus, CI values of Layout #1 for Scenario #1 is slightly less than that of Scenario #2. On the other hand, increasing segment delivery interval for only 1 day in Scenario #3 could significantly (i.e., about 6.7%) increase the cost of Layout #1. This is because of the fact that the cost lost by segment stock-out considerably exceeded the cost saved for using less off-site storage. Note that SWDF is not able to account for the impact of construction planning variables on the efficiency of the layout.
- Comparing Layout #1 and #16 shows that main differences between the layouts, which can impact the costs, are the location and size of the segment storage. Having a smaller size of the segment storage in Layout #16 led to less costs for the mobilization, demobilization and maintenance as well as less direct and indirect costs due to improving production rate by positioning it closer to the shaft. On the other hand, the smaller on-site storage exposes the project to extra cost for off-site storage. This extra cost can be reduced when the production rate is improved by positing the segment storage closer to the shaft (see Figure 5 (a) for further information). As a result of cost

analysis performed by simulation, Layout #16 has less (between 0.9% and 1.6%) costs than Layout #1 under the three scenarios; SWDF is not able to perform this detailed analysis on the cost impact of facility size and location.

To further substantiate the merit of this framework, the case study was experimented with by using the SWDF approach with the same GA parameters and weights but with no preference given for the facility size and inclusion area soft constraints. The optimum layout from SWDF is depicted in Figure 5 (d). FI of this layout was measured as 0.7448 (15.4% less functionality than the Layout #1), which is because (1) SWDF cannot consider inclusion/exclusion area soft constraints, and positioned the spoil pile outside of the desired loading area, (2) SWDF cannot consider facility size preferences and selected smaller sizes for spoil pile and segment storage to better satisfy their closeness constraints by positioning them closer to the shaft, and (3) SWDF models the closeness constraints in a way that satisfaction of all the constraints varies linearly by distance, which caused less desirable locations for some facilities. For instance, the propane tank should be far from the shaft due to safety, and close to the site trailer for its use. However, SWDF positioned the propane tank close to the parking rather than the trailer to be farther to shaft, which compromised its distance from the trailer . Similarly for the tool crib, the significance of positioning it far from the crane working zone (due to safety) compromised its closeness constraint to the shaft, and caused a less desirable location for the tool crib, which is very far from the shaft. To determine VI value of this layout, its CI value was experimented with using simulation under Scenario 1. Then, the CI value of the layout was experimented with using simulation under Scenario 1. This value was 0.9337, which is less than that of Layout 1. This is because of less mobilization, demobilization, and maintenance costs of the spoil pile, and segment storage, and their closer distance to the shaft. However, the VI value of the layout was calculated as 0.7977, which is 14.4% less than that of Layout #1. Hence, SWDF resulted in a less efficient layout than the proposed method.

Overall, this case study demonstrated the benefits of the developed framework over the existing methods, summarized as follows: (1) It accounts for more factors such as construction planning variables that can influence the cost efficiency of the site layout, it captures their complex dependency, and it determines the significance of their impacts and on the project costs through simulation; (2) It can consider facility size variability in optimization, and evaluates the impact of facility size on the project functionality and cost through FI and CI, respectively; (3) It can model resource interactions and uncertainties inherent in construction projects through simulation; (4) It can model various types of constraints for positioning facilities and evaluate them more realistically than SWDF; (5) It evaluates and selects the optimum layout based on both functionality and cost, which enables the planner to evaluate satisfaction of the subjective constraints, and quantify the cost impacts of the layout; and (6) It allows for experimenting with different construction planning scenarios, enabling the planner to identify the most efficient construction plan along with the layout plan.

Verification and Validation of the Model

The model is comprised of GA optimization and simulation modeling components. A variety of verification and validation tests described by Sargent (2003) were performed to determine validity of these components. Summary of these tests are presented in Table 7.

Conclusion

This paper outlined a framework employing GA and simulation for decision making for site layout planning. The main contributions of this study are to:

- develop a novel method to qualitatively evaluate the functionality of site layouts by modeling distance constraints more realistically and considering the size and location preferences; and

- forecast the cost efficiency of site layouts using simulation, which can more realistically quantify the mutual impacts of site layout and construction operation on the project costs by modeling complex construction processes, inherent uncertainties, utilized resources and dynamic interactions between different parameters.

The developed framework was implemented in the site layout planning process for a tunneling project that further substantiated how it could improve the deficiency of the existing methods. Analysis of the results showed that simple changes in site layout or construction plan variables can impact efficiency of the site layout. This impact is appropriately captured in the model that assists planners in decision making. This framework is more suitable for layout planning of sites where satisfying subjective constraints and cost efficiency of the layout are both crucial. Future studies can be followed by experimenting with other heuristic optimization methods to determine their adaptabilities compared to GA.

Acknowledgement

The researchers would like to extend their appreciation to the City of Edmonton for their vital cooperation during this study. This research is supported by the NSERC Industrial Research Chair in Construction Engineering and Management, IRCPJ 195558-10.

References

AbouRizk, S. (2010). "Role of Simulation in Construction Engineering and Management." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000220, 1140-1153.

Alanjari, P., Razavialavi, S. and AbouRizk, S., 2014. "A simulation-based approach for material yard laydown planning." *Automation in Construction*, Volume 40, pp. 1-8.

Azadivar, F. and Wang, J., 2000. "Facility layout optimization using simulation and genetic algorithms." *International Journal of Production Research*, pp. 4369-4383.

Elbeltagi, E., Hegazy, T., and Eldosouky, A. (2004). "Dynamic Layout of Construction Temporary Facilities Considering Safety." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2004)130:4(534), 534-541.

Hajjar, D., and AbouRizk, S. M. (1996). “ Building a special purpose simulation tool for earth moving operations. ” Proc., 28th Winter Simulation Conf., IEEE, Piscataway, NJ, 1313 – 1320.

Lien, L. C. and Cheng, M. Y., 2012. "A hybrid swarm intelligence based particle-bee algorithm for construction site layout optimization." *Expert Systems with Applications,* 39(10), pp. 9642-9650.

Mitchell, M., 1999. *An Introduction to Genetic Algorithm.* Cambridge, Massachusetts, London, England: The MIT Press.

Ning, X., Lam, K.-C. and Lam, . M. C.-K., 2010. "Dynamic construction site layout planning using max-min ant system." *Automation in Construction,* 19(1), pp. 55–65.

Osman, H. M., Georgy, M. E. and Ibrahim, M. E., 2003. "A hybrid CAD-based construction site layout planning system using genetic algorithms." *Automation in Construction,* Volume 12, pp. 749-764.

RazaviAlavi, S. and AbouRizk, S., 2014. *An Integrated Simulation Model for Site Layout Planning of Tunneling Projects.* Proc. of the 13th Int. Conference on Modeling and Applied Simulation; Bruzzone, De Felice, Massei, Merkuryev, Solis, Zacharewicz Eds. pp. 46-53.

RazaviAlavi, S. and AbouRizk, S., 2015. "A hybrid simulation approach for quantitatively analyzing the impact of facility size on construction projects." *Automation in Construction,* Volume 60, pp. 39-48.

Rosenblatt, M., 1986. "The dynamics of plant layout." *Management Science,* 32(1), pp. 76-86.

Sadeghpour, F., Moselhi, O., and Alkass, S. (2006). "Computer-Aided Site Layout Planning." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2006)132:2(143), 143-151.

Sargent, R. G. 2003. *Verification and validation of Simulation Models*. Proceedings of the 2003 Winter Simulation Conference, IEEE, Piscataway, NJ, 37-48.

Smutkupt, U. and Wimonkasame, S., 2009. *Plant layout design with simulation.* The International MultiConference of Engineers and Computer Scientists, Vol. 2, 18-20.

Tommelein, I. D., 1999. *Travel-time simulation to locate and staff temporary facilities under changing construction demand.* Proc., 31st Winter Simulation Conf., IEEE, Piscataway, NJ, vol. 2, 978-984.

Zhang, H. and Wang, J. (2008). "Particle Swarm Optimization for Construction Site Unequal-Area Layout." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2008)134:9(739), 739-748.

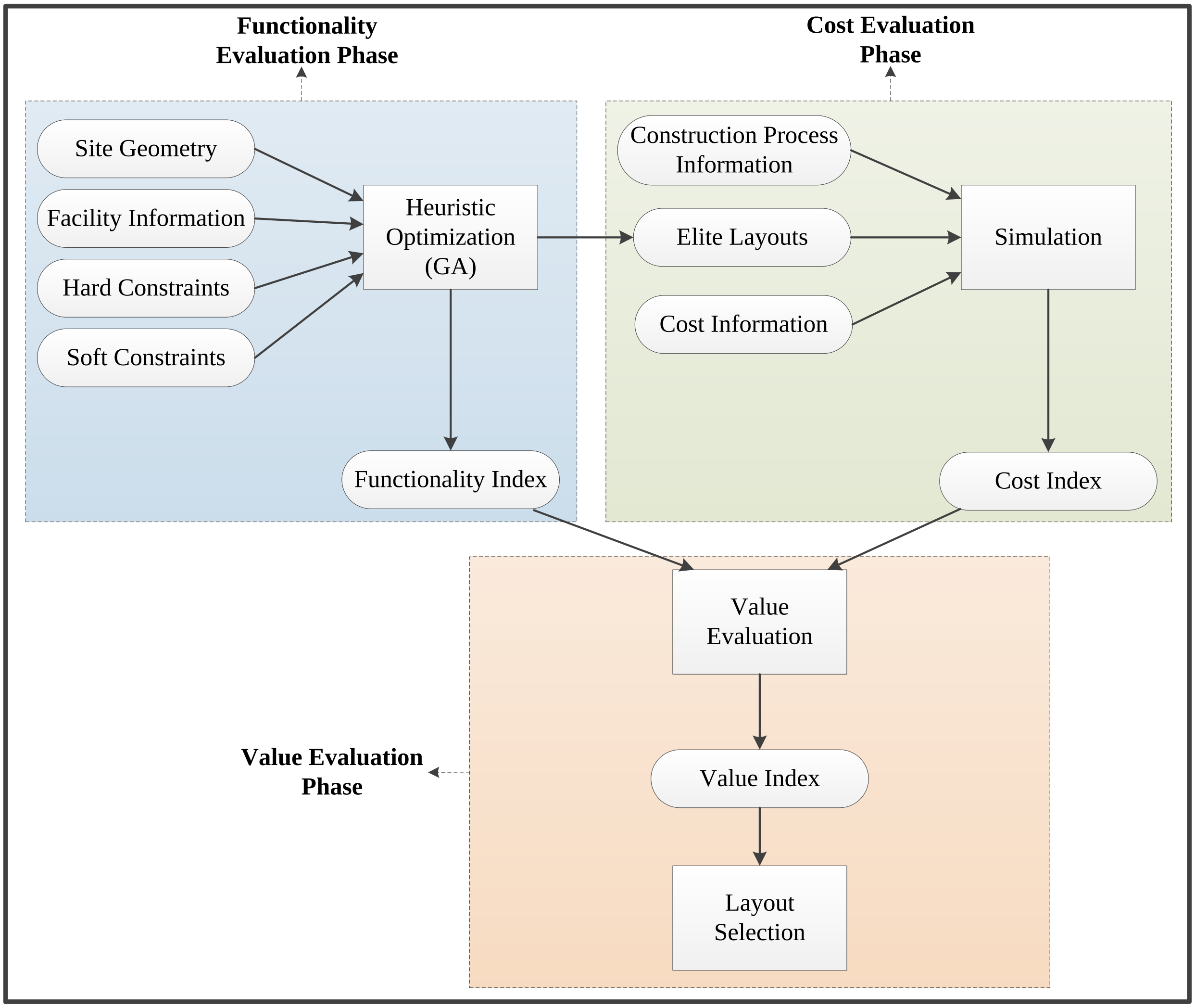

Figure 1. Overview of the decision making framework

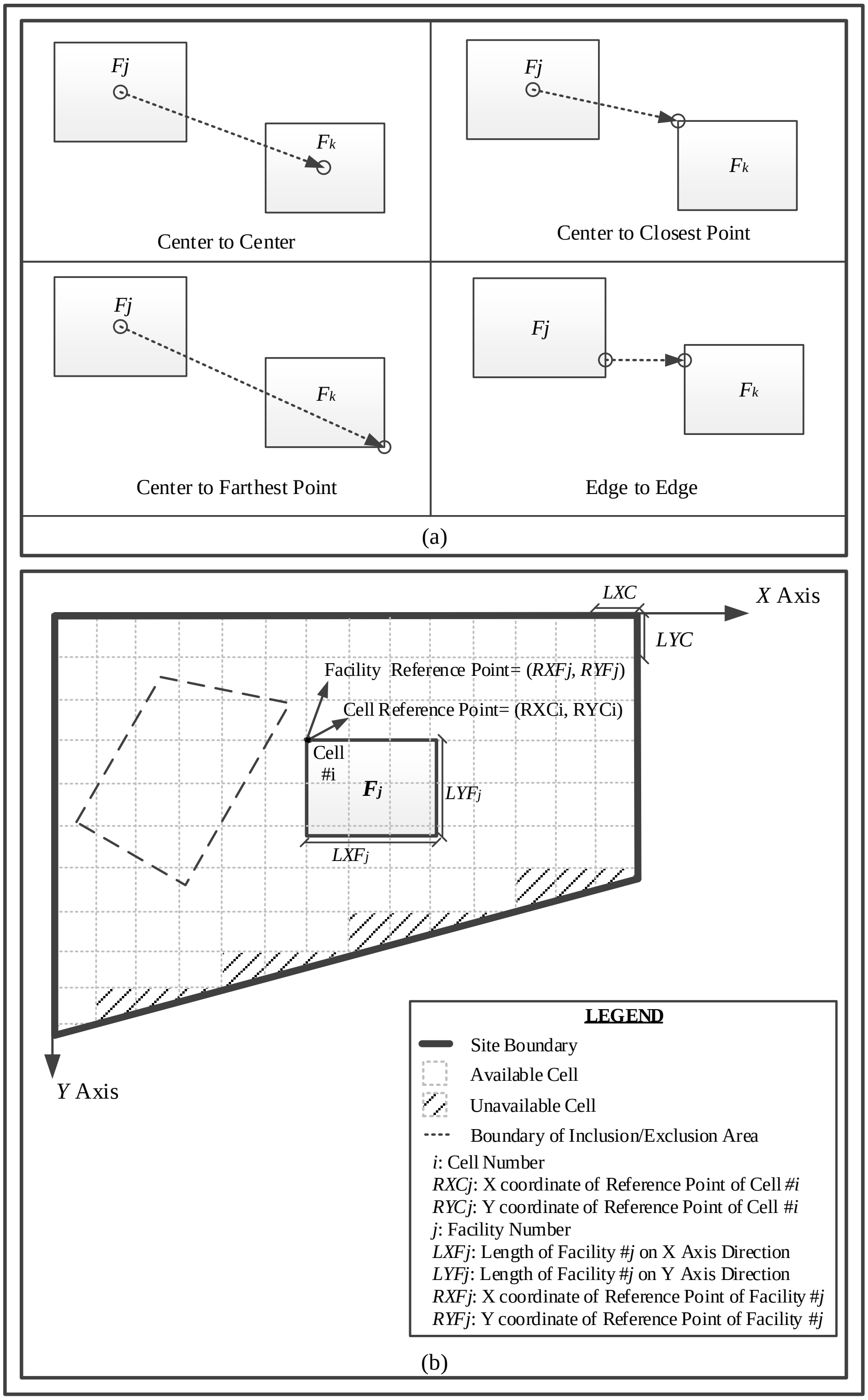

Figure 2. (a) Schematic view of distance measurement types, and (b) site boundaries, gridlines, facilities, and areas

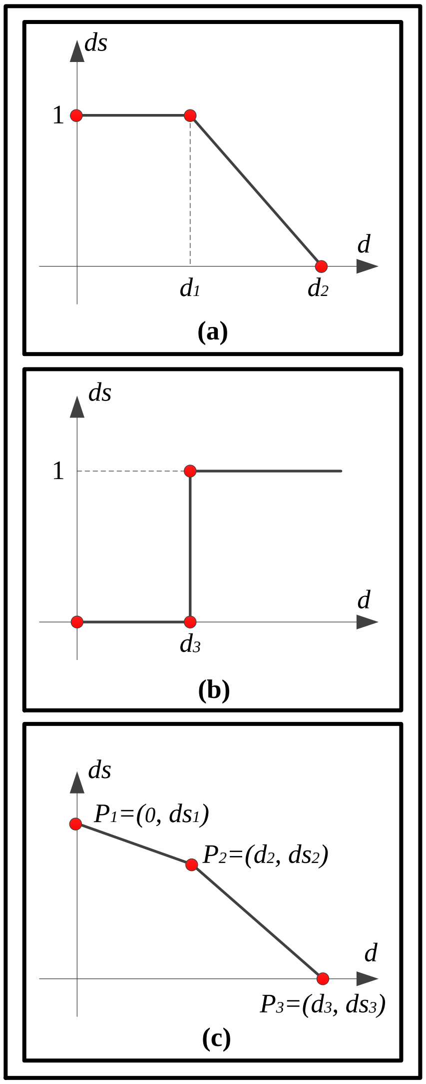

Figure 3. The form of the distance constraint satisfaction

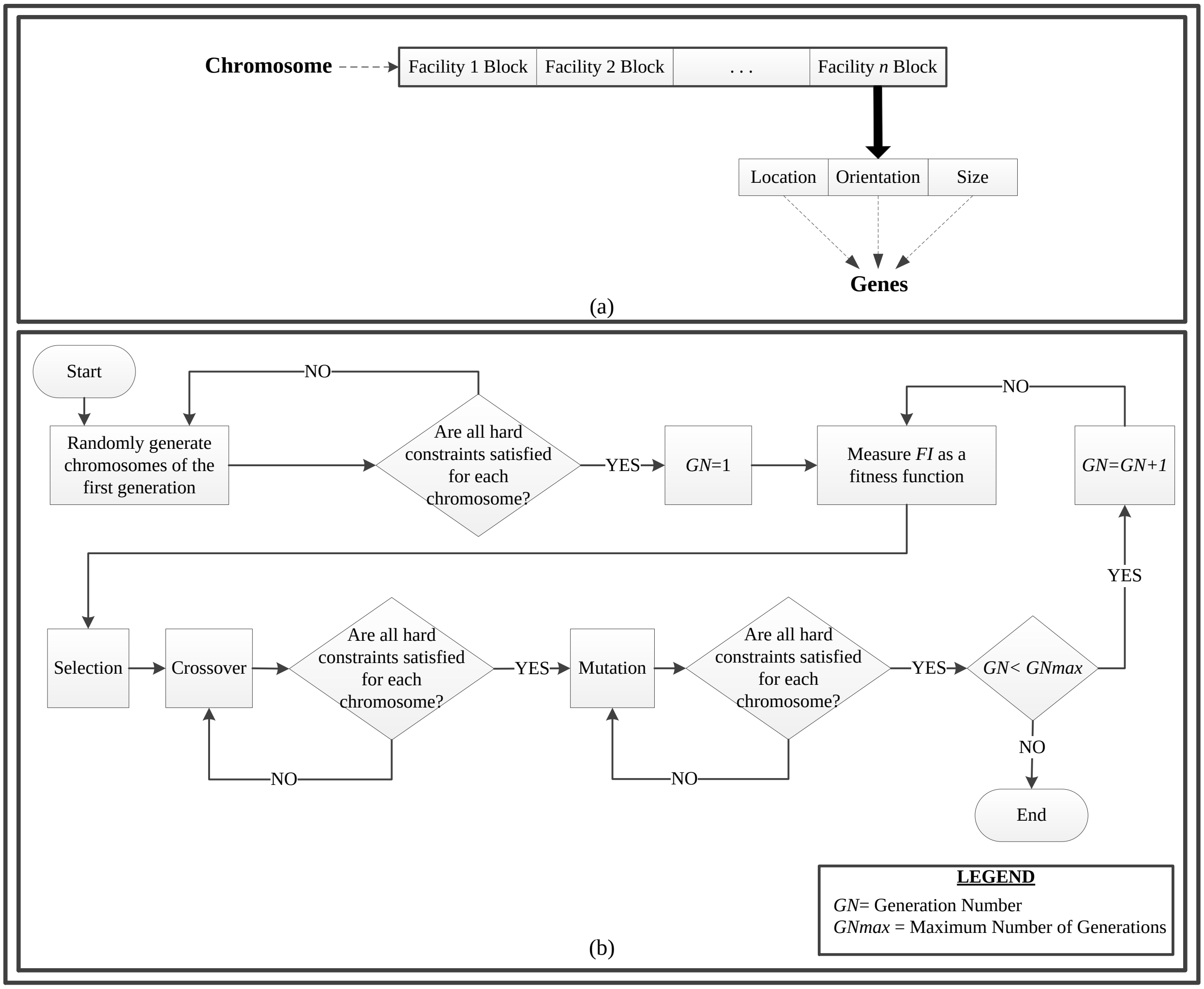

Figure 4. (a) Composition of the chromosomes in GA, and (b) GA optimization process

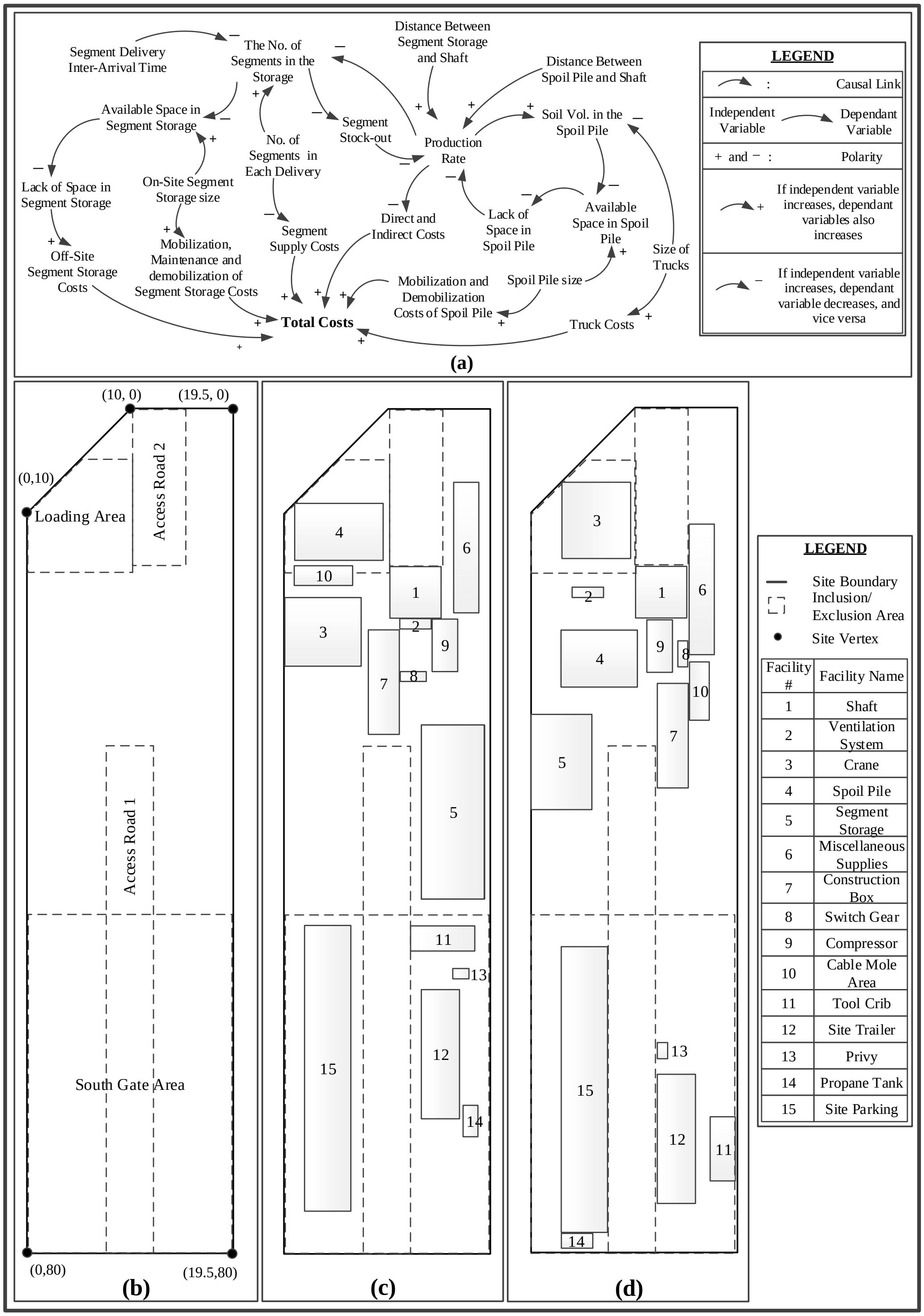

Figure 5 (a): Dependencies among variables in site layout planning of tunneling projects (b): site overview, (c): optimum layout from the developed framework, and (d) optimum layout from SWDF approach

Table 1. Specifications of the facilities

Facility #	Facility Name	Location Type	Orientation Type	Size Type	Size 1 (m×m)/ Ss	Size 2 (m×m)/ Ss	Size 3 (m×m)/ Ss	Size 4 (m×m)/ Ss
1	Shaft	Fixed (RXF=10, RYF=15)[a]	Fixed	Fixed	5×5/ NA	NA[d]	NA	NA
2	Crane	Variable	Variable	Fixed	6.6×7.3/ NA	NA	NA	NA
3	Spoil Pile	Variable	Variable	Variable (W=7)[c]	8.5×5.5/ 1	7.25×5.5/ 0.9	6×5.5/ 0.8	NA
4	Segment Storage	Variable	Variable	Variable (W=5)[c]	6×16.5/ 1	6×14/ 0.95	6×11.5/ 0.9	6×9/ 0.8
5	Miscellaneous Supply Storage	Variable	Variable	Fixed	2.5×12.5/ NA	NA	NA	NA
6	Construction Box	Variable	Variable	Fixed	3×10/ NA	NA	NA	NA
7	Switch Gear	Variable	Variable	Fixed	1×2.5/ NA	NA	NA	NA
8	Compressor	Variable	Variable	Fixed	2.5×5/ NA	NA	NA	NA
9	Cable Mole Area	Variable	Variable	Fixed	1.8×5.5/ NA	NA	NA	NA
10	Tool Room	Variable	Variable	Fixed	2.4×6.1/ NA	NA	NA	NA
11	Site Trailer	Variable	Fixed (0 degree)[b]	Fixed	3.7×12.3/ NA	NA	NA	NA
12	Privy	Variable	Variable	Fixed	1×1.5/ NA	NA	NA	NA
13	Propane Tank	Variable	Variable	Fixed	1.4×3/ NA	NA	NA	NA
14	Site Parking	Variable	Fixed (0 degree)[b]	Fixed	4.4×27/ NA	NA	NA	NA
15	Ventilation	Variable	Variable	Fixed	1×3/ NA	NA	NA	NA

[a] Coordinates of the reference point if the facility is fixed-location
[b] Degree of rotation if the facility is fixed-orientation
[c] Weight of size satisfaction if facility is variable-size
[d] "Not Applicable"

Table 2. Distance hard constraints for positioning facilities

Facility 1	**Facility 2**	**Distance Type**	**D_{min} (m)**	**D_{max} (m)**
Crane	Shaft	Center to Center	NA	20
Crane	Spoil Pile	Center to Farthest Point	NA	20
Crane	Site Trailer	Center to Closest Point	20	NA
Segment Storage	All Facilities	Edge to Edge	2	NA

Table 3. Inclusion/exclusion area hard constraints for positioning facilities

Area Name	**Facility Name**	**Inclusion/ Exclusion**	**Coordinates of Area Vertices**
Access Road 1	All Facilities	Exclusion	(7.5,32), (12,32), (12,80) and (7.5,80)
Access Road 2	All Facilities	Exclusion	(10, 0), (10,15), (15,15), and (15,0)

Table 4. Distance soft constraints for positioning facilities

First Facility	**Second Facility**	**Distance Type**	**Weight**	**D_S (Coordinates of Three Points)**
Shaft	Spoil Pile	Center to Center	10	(0,1), (5,1) and (20,0)
Shaft	Segment Storage	Center to Center	8	(0,1), (10,1) and (60,0)
Crane	Segment Storage	Center to Farthest Point	3	(0,1), (20,1) and (20,0)
Shaft	Cable Mole Area	Center to Closest Point	5	(0,1), (5,1) and (25,0)
Shaft	Tool Room	Center to Closest Point	5	(0,1), (10,1) and (60,0)
Shaft	Compressor	Center to Closest Point	6	(0,1), (5,1) and (15,0)
Shaft	Ventilation System	Center to Closest Point	10	(0,1), (4,1) and (8,0)
Switch Gear	Construction Box	Center to Closest Point	2	(0,1), (2,1) and (10,0)
Cable Mole Area	Construction Box	Center to Closest Point	2	(0,1), (3,1) and (20,0)
Switch Gear	Cable Mole Area	Center to Closest Point	2	(0,1), (3,1) and (20,0)
Privy	Site Trailer	Center to Closest Point	6	(0,1), (2,1) and (10,0)
Shaft	Propane Tank	Center to Closest Point	9	(0,0), (30,0) and (70,1)
Shaft	Site Trailer	Center to Center	3	(0,1), (20,1) and (60,0)
Shaft	Miscellaneous Supply Storage	Center to Closest Point	6	(0,1), (10,1) and (40,0)
Propane Tank	Site Trailer	Center to Closest Point	10	(0,1), (1,1) and (5,0)
Shaft	Construction Box	Center to Closest Point	4	(0,1), (5,1) and (25,0)
Shaft	Switch Gear	Center to Closest Point	4	(0,1), (5,1) and (25,0)
Crane	Tool Room	Center to Closest Point	10	(0,0), (20,0) and (20,1)
Privy	Shaft	Center to Center	1	(0,1), (30,1) and (70,0)
Parking	Site Trailer	Center to Center	4	(0,1), (10,1) and (30,0)
Compressor	Construction Box	Center to Closest Point	2	(0,1), (3,1) and (25,0)

Table 5. Inclusion/exclusion area soft constraints for positioning facilities

Area Name	Facility Name	Inclusion/ Exclusion	Weight	Coordinates of Area Vertices
Loading Area	Spoil Pile	Inclusion	5	(5,5), (10,5), (10,15.5), (0,15.5) and (0,10)
South Gate Area	Parking	Inclusion	8	(0,48), (19.5,48), (19.5,80) and (0,80)
South Gate Area	Site Trailer	Inclusion	8	(0,48), (19.5,48), (19.5,80) and (0,80)

Table 6. Elite layouts

Layout #	Spoil Pile Size	Distance of Spoil Pile to Shaft (m)	Segment Storage Size	Distance of segment storage to shaft (m)	FI	Scenario 1		Scenario 2		Scenario 3	
						CI	VI	CI	VI	CI	VI
#1	8.5×5.5	9.2	6×16.5	21	0.8805[a]	0.9442	0.9325[c]	0.9456	0.9311	1	0.8805
#2	8.5×5.5	9.2	6×16.5	21	0.8716	0.9442	0.9231	0.9456	0.9217	1	0.8716
#3	8.5×5.5	9.2	6×16.5	21	0.8666	0.9442	0.9178	0.9456	0.9164	1	0.8666
#4	8.5×5.5	9.2	6×16.5	21	0.8666	0.9442	0.9178	0.9456	0.9164	1	0.8666
#5	8.5×5.5	9.2	6×16.5	21	0.8666	0.9442	0.9178	0.9456	0.9164	1	0.8666
#6	8.5×5.5	9.2	6×16.5	21	0.8666	0.9442	0.9178	0.9456	0.9164	1	0.8666
#7	8.5×5.5	9.2	6×16.5	21	0.8665	0.9442	0.9177	0.9456	0.9163	1	0.8665
#8	8.5×5.5	9.2	6×14	19.8	0.8662	0.9394	0.9220	0.9449	0.9167	0.9912	0.8739
#9	8.5×5.5	9.2	6×16.5	21	0.8647	0.9442	0.9158	0.9456	0.9144	1	0.8647
#10	8.5×5.5	9.2	6×16.5	21	0.8643	0.9442	0.9154	0.9456	0.9140	1	0.8643
#11	8.5×5.5	9.2	6×16.5	21	0.8643	0.9442	0.9154	0.9456	0.9140	1	0.8643
#12	8.5×5.5	9.2	6×16.5	21	0.8643	0.9442	0.9154	0.9456	0.9140	1	0.8643
#13	8.5×5.5	9.2	6×16.5	21	0.8643	0.9442	0.9154	0.9456	0.9140	1	0.8643
#14	8.5×5.5	9.2	6×16.5	21	0.8642	0.9442	0.9153	0.9456	0.9139	1	0.8642
#15	8.5×5.5	9.2	6×16.5	21	0.8638	0.9442	0.9149	0.9456	0.9135	1	0.8638
#16	8.5×5.5	9.2	6×9	17.3	0.8637	0.9340[b]	0.9248	0.9368	0.9220	0.9841	0.8776
#17	8.5×5.5	9.2	6×16.5	21	0.8636	0.9442	0.9146	0.9456	0.9133	1	0.8636
#18	8.5×5.5	9.2	6×11.5	18.6	0.8635	0.9343	0.9242	0.9389	0.9197	0.9896	0.8725
#19	8.5×5.5	9.2	6×16.5	21	0.8629	0.9442	0.9139	0.9456	0.9125	1	0.8629
#20	8.5×5.5	9.2	6×16.5	21	0.8617	0.9442	0.9126	0.9456	0.9113	1	0.8617
#21	8.5×5.5	9.2	6×16.5	21	0.8617	0.9442	0.9126	0.9456	0.9112	1	0.8617
#22	8.5×5.5	9.2	6×16.5	21	0.8603	0.9442	0.9112	0.9456	0.9098	1	0.8603
#23	8.5×5.5	9.2	6×16.5	21	0.8603	0.9442	0.9112	0.9456	0.9098	1	0.8603
#24	8.5×5.5	9.2	6×16.5	21	0.8603	0.9442	0.9112	0.9456	0.9098	1	0.8603
#25	8.5×5.5	9.2	6×16.5	21	0.8603	0.9442	0.9112	0.9456	0.9098	1	0.8603
#26	8.5×5.5	9.2	6×16.5	21	0.8603	0.9442	0.9112	0.9456	0.9098	1	0.8603
#27	8.5×5.5	9.2	6×16.5	21	0.8597	0.9442	0.9105	0.9456	0.9092	1	0.8597
#28	8.5×5.5	9.2	6×16.5	21	0.8583	0.9442	0.9090	0.9456	0.9076	1	0.8583
#29	7.25×5.5	10.3	6×16.5	21	0.8572	0.9407	0.9112	0.9426	0.9094	0.9991	0.8579
#30	8.5×5.5	9.2	6×16.5	21	0.8568	0.9442	0.9074	0.9456	0.9061	1	0.8568
#31	8.5×5.5	9.2	6×16.5	21	0.8561	0.9442	0.9068	0.9456	0.9054	1	0.8561
#32	8.5×5.5	9.2	6×16.5	21	0.8545	0.9442	0.9050	0.9456	0.9036	1	0.8545
#33	8.5×5.5	9.2	6×16.5	21	0.8534	0.9442	0.9038	0.9456	0.9025	1	0.8534
#34	7.25×5.5	9.7	6×16.5	21	0.8523	0.9478	0.8992	0.9456	0.9013	0.9902	0.8607
#35	8.5×5.5	9.2	6×16.5	21	0.8506	0.9442	0.9008	0.9456	0.8995	1	0.8506

[a] Highest FI

[b] Lowest CI
[c] Highest VI

Table 7. Tests performed for verification and validation of the model

Test description	Purpose of the test	Summary of the test process	Test results
Comparison to other models, in which the results of the model being validated are compared to results of other (valid) models such as simple cases with known results.	Validation of GA producing near optimum solutions	The GA program developed in this model was tested by comparing its results to the known results of some simple site layout cases.	The GA results were identical or very close to the known results of various simple cases. For instance, a case with only shaft, segment storage, spoil pile, crane and propane tank was tested. The result was positioning spoil pile, segment storage and crane as close as possible, and propane tank as far as possible from the shaft, which was expected considering the defined constraints.
Dynamic testing, in which the computer program is executed under different conditions and the obtained values are used to determine if the computer program and its implementations are correct.	Validation of GA checking the hard constraints and calculating FI correctly	The user interface of the developed program can visualize the layouts generated by GA and illustrate the FI value as well as the facility location and size information. Using this feature, satisfaction of the hard constraints and correctness of FI calculation were tested.	This test was performed for various layouts generated by GA. Their FI values were equal to hand calculated values, and all the constraints including non-overlapping, being inside the boundary, and other user-defined constraints were satisfied correctly.
Traces, in which the behavior of different types of specific entities in the model are traced through the model to determine if the model's logic is correct.	Validation of the simulation model mimicking the tunneling process correctly	The simulation tool has a trace window, which can print the information pertaining to the events happening in the simulation model. This information was analyzed and compared to the results from hand calculation.	The information such as the time and duration of the activities taking place in the tunneling operation, as well as the changes occurring in the available number of segments in the segment storage and available volume of the dirt in the spoil pile was traced and verified to be equal to the results of hand calculation.
Extreme condition tests, in which the model structure and output is tested to be plausible for any extreme and unlikely combination of levels of factors in the system.		The model was tested for extreme conditions such as having zero capacity for the spoil pile, segment storage, and trucks, and having no segment delivery.	The outputs were plausible for the tested extreme conditions. For instance, no segment delivery, or zero capacity for spoil pile resulted in a zero tunnelling production rate as expected.
Parameter variability - sensitivity analysis, in which changing the values of the input of a model should have the same effect in the model as in the real system.		This test was performed by changing different variables such as size and interval time of segment delivery, the number and size of the trucks, and the capacity of the segment storage and spoil pile.	The impacts of the tested changes on project cost and time were as expected in the real system. For instance, by increasing the capacity of the segment storage, the extra storage cost was reduced as expected, or by reducing the capacity of spoil pile, the total delay time due to lack of space in the spoil pile was increased as expected.
Operational graphics, in which values of various performance measures are shown graphically as the model runs through time.		This test was performed using graphs produced in the model for the available number of segments, and the available volume of soil.	The graphs showed that the changes in the available number of segments and available volume of soil were as expected. For instance, in the chart, the number of segments was increased when the segment delivery was scheduled.