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1 **Genetic Algorithm–Simulation Framework for Decision Making in Construction Site**

2 **Layout Planning**

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11  
12 **Abstract**

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

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

## 29 **Introduction**

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

36 SLP has been widely studied in the literature. The majority of past research focused on finding  
37 the optimum location for facilities (e.g., Sadeghpour, et al. (2006) and Zhang and Wang (2008)).  
38 In past research, different constraints that are affected by the location of facilities, such as on-site  
39 transportation costs, safety, accessibility, and planners' preferences, have been considered.  
40 Conventionally, the sum of weighted distance function (SWDF) has been utilized to evaluate the  
41 desirability of layouts, which is defined as  $\sum w \times d$ , where  $w$  reflects the weight of interactions or  
42 closeness factors between facilities, and  $d$  represents the distance between facilities (Rosenblatt  
43 1986). Different approaches exist for defining  $w$ : 1) quantitative approaches (e.g., Zhang and Wang  
44 (2008)), that only consider the transportation cost and define  $w$  as the transportation cost per unit  
45 of distance based on the frequency and means of transportation between facilities, and 2)  
46 qualitative approaches (e.g., Elbeltagi, et al. (2004)), in which  $w$  is the closeness weight between  
47 facilities that can reflect the transportation cost, safety and environmental hazards, and/or any other  
48 closeness constraints between facilities

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

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

53    • The efficiency of SWDF in practice is in question. The weights considered in SWDF can reflect  
54    the impact of facility locations on the on-site transportation cost, but cannot quantify their impacts  
55    on the entire project. For instance, a long distance between two facilities not only entails more  
56    material transportation costs between them, but also may result in late delivery of the material,  
57    which can interrupt the workflow and cause idleness of the resources demanding the material for  
58    production. This will further lead to loss of production rate and costs. These impacts depend not  
59    only on the transportation distance but also on the number of material handlers, their speed, and  
60    the production cycle time of the resources. In addition, construction projects contain dynamic  
61    processes with inherent uncertainties such as variation in production rate and duration of the  
62    activities. The inability of SWDF to model these factors, and quantify the consequences of the on-  
63    site transportation on the project, can result in planning inefficient layouts; this was substantiated  
64    by Alanjari, et al. (2014).

65    • SWDF only considers the locations of the facilities as a variable, and overlooks size of the facilities  
66    as another factor that can significantly impact the productivity and cost of projects. On construction  
67    sites, the size of some facilities which predominantly maintain materials (e.g. material storages),  
68    is variable and should be determined through a site layout planning process. The size of such  
69    facilities can influence the material flow and project costs (RazaviAlavi and AbouRizk, 2015). For  
70    instance, insufficient size of material storage on the site may entail extra costs for changing the  
71    material delivery plan, or storing materials off the site and transporting them to the site when space  
72    is available. Facility size is more critical on congested sites, in which the planner may not be able  
73    to provide sufficient size for all facilities, and has to shrink the size of some facilities or position  
74    them in unfavorable areas. In addition, allocating a facility more space than required may incur

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

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

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

## 92 **Decision Making Framework**

93 The proposed framework for decision making on SLP consists of three phases: 1) Functionality  
94 Evaluation Phase (FEP), 2) Cost Evaluation Phase (CEP), and 3) Value Evaluation Phase (VEP).  
95 The overview of the framework is depicted in Figure 1. In the FEP, the site geometry and facility  
96 information including the type, shape and size of the facilities, as well as hard and soft constraints  
97 (which are discussed in detail later) are the inputs of the heuristic optimization. The reason for

198 using heuristic optimization is that there are a large number of possible solutions in SLP. In this  
199 study, genetic algorithm (GA) is adopted as an optimization method to heuristically search for the  
100 near-optimum layouts evaluated by the predefined fitness function. GA's fitness function is the  
101 Functionality Index (FI) that addresses the satisfaction level of different constraints including  
102 distance constraints, facility size, and favorable/unfavorable areas for positioning facilities. Using  
103 GA, a set of elite layouts, which are feasible (i.e., completely satisfy hard constraints) and qualified  
104 (i.e., satisfy soft constraints to the highest levels), are identified and imported to CEP. In CEP, the  
105 cost of the elite layout is evaluated using simulation. Simulation is a suitable tool for mimicking  
106 construction processes and quantitatively measuring important parameters such as project time,  
107 cost and productivity. Application of simulation is more effective in modeling projects with  
108 uncertainties, technical or methodical complexity, and repetitive tasks (AbouRizk, 2010), which  
109 are common in most construction projects. Simulation has been successfully applied in quantifying  
110 the impact of facility locations on transportation time (e.g., Tommelein (1999), and Azadivar and  
111 Wang (2000)) and the impact of facility size on the project cost (RazaviAlavi and AbouRizk,  
112 2015). Modeling resource interactions (Alanjari, et al., 2014) and providing the planners with more  
113 information such as total time in system and resource utilization (Smutkupt and Wimonkasame,  
114 2009) were recognized as the prominent advantages of using simulation in SLP.

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

120 **Functionality Evaluation Phase (FEP)**

121 The FEP phase aims to produce feasible layouts and heuristically find the most qualified ones.

122 The inputs, procedures and assumptions of this phase are as follows.

123 **Site geometry**

124 The geometry of the site should be specified to identify the places that facilities can be placed.

125 In this study, any polygon shape can be considered as the site boundaries by identifying coordinates

126 of the polygon's vertices. To reduce the searching space for positioning facilities, underlying

127 gridlines are adopted. Gridlines create cells on which facilities can be positioned. The size of the

128 cells depends on the size of the site and facilities, and the accuracy that the planner seeks. The

129 common suggestion for the cell size is the smallest dimension of the facilities.

130 **Facility information**

131 This information comprises the attributes of the facilities that should be determined as inputs,

132 such as the type, shape and size of each facility. Different types of facilities can be identified: a)

133 predetermined or movable location, b) predetermined or variable orientation, and c) predetermined

134 or variable size. Any attribute (i.e., location, orientation, and size) of a facility that is variable will

135 be determined through GA optimization. In this study, the shape of the facilities is limited to

136 rectangles, and the orientation is limited to 0 and 90 degrees. Considering these assumptions, the

137 size of the facilities is specified by their length and width.

138 **Hard constraints**

139 Hard constraints are the ones that must be satisfied. Any layout that does not satisfy the hard

140 constraints is considered unfeasible. The GA optimization checks satisfaction of all hard

141 constraints to prevent producing unfeasible layouts. The following hard constraints are considered

142 in this study:



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

150 The assumption for positioning facilities is that the top left corner of the facility is positioned

151 at the top left corner of the designated cell. The cells and facilities are numbered to specify which

152 cell is designated to which facility. The top left corner of the cells and facilities are considered

153 their reference points, and the Cartesian coordinate system is used to formulate the position of the

154 facility as shown in Figure 2(b).

155 Given the fact that the coordinates of the cell corners can be calculated using the coordinates of

156 the site vertices and the cell size, the coordinates of the reference point and the center point of the

157 facilities are calculated as follows (once Cell #i is designated to Facility #j ( $F_j$ )):

$$\text{Reference point coordinates: } (RXF_j, RYF_j) = (RXC_i, RYC_i) \quad (1)$$

$$\text{Center point coordinates: } (CXF_j, CYF_j) = (RXF_j + LXF_j/2, RYF_j + LYF_j/2) \quad (2)$$

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

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

$$RXF_{X_{\min}} + LXF_{X_{\min}} \leq RXF_{X_{\max}}; \text{ OR} \quad (3)$$

$$R_{XF_{Y_{\min}}} + L_{XF_{Y_{\min}}} \leq R_{XF_{Y_{\max}}} \quad (4)$$

163 where between two facilities,  $F_{X_{\min}}$  is the facility with minimum RXF,  $F_{X_{\max}}$  is the facility with  
 164 maximum RXF,  $F_{Y_{\min}}$  is the facility with minimum RYF, and  $F_{Y_{\max}}$  is the facility with maximum  
 165 RYF.

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

168 • For inclusion/exclusion of a facility in/from the Area A, satisfying both:

169 - No edges of the facility have any intersections with edges of the area; and

170 - A point of the facility (e.g., its top left corner) is inside/outside the area.

171 • For minimum or maximum distance constraint ( $D_{\min/\max}$ ) between two points of Facility #j and #k,

172 Euclidean method is used for measurement, and the corresponding equation should be satisfied:

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

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

173 - where  $a = (x_j, y_j)$  and  $b = (x_k, y_k)$  are the specified points of facility #j and #k,

174 respectively, for measuring the distance (see Figure 2(a)).

175 • 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)

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

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

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

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

177

178 **Soft constraints**

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

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

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

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

192 **Distance constraint satisfaction (ds)**

193  $ds$ , which varies between 0 and 1, is a function of distance between two facilities measured from  
194 the edges or the selected points using the Euclidean method. For the closeness constraints that  
195 intend to position two facilities close to each other, the level of satisfaction is reduced by increasing  
196 the distance. On the other hand, for the closeness or safety constraints that intend to position two  
197 facilities far from each other, the level of satisfaction is increased by increasing the distance.  
198 However, as discussed earlier, the form of satisfaction varies due to the different nature of each  
199 constraint. For example, as seen in Figure 3 (a), once it is desirable to position two facilities close

200 to each other, within a certain distance ( $d_1$ ), the constraint can be completely satisfied. Farther than  
 201  $d_1$ , the level of satisfaction can be reduced by increasing the distance until it reaches  $d_2$ . Distance  
 202 farther than  $d_2$  does not satisfy that constraint. Figure 3 (b) illustrates the example of a distance  
 203 constraint to prevent falling objects from a crane on a facility. If the facility is positioned farther  
 204 than the distance of  $d_3$ , the constraint is completely satisfied. Otherwise, its level of satisfaction is  
 205 zero. In general, assuming that  $ds$  varies linearly by  $d$ , the form of  $ds$  can be identified by  
 206 determining the coordinates of the points connected to each other consecutively. Given the fact  
 207 that there is no limitation for the number of the points, most forms can be defined by three points  
 208 (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  
 209 (b). The coordinates of the points (i.e.,  $P_x$  and  $P_y$ ) represent  $d$  and  $ds$ , respectively. It should be  
 210 noted that  $P_x$  must be 0 for the first point. For a given  $d$  as a distance measured between two  
 211 facilities, the distance satisfaction  $ds$  can be calculated using the following equation:

$$ds = \begin{cases} \frac{ds_2 - ds_1}{d_2} \times d + ds_1 & \text{if } 0 \leq d \leq d_2 \\ \frac{ds_3 - ds_2}{d_3 - d_2} \times d + ds_3 - \frac{ds_3 - ds_2}{d_3 - d_2} \times d_3 & \text{if } d_2 < d < d_3 \\ ds_3 & \text{if } d \geq d_3 \end{cases} \quad (12)$$

212 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)),  
 213 the highest value is considered an assumption for  $ds$ .

214 **Size constraint satisfaction (Ss)**

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

220 0 and 1. For example, if the planner defines three sizes for a facility and assigns 10 to the weight,  
221 and 0.2, 0.5, and 1 as  $S_s$  to each size, respectively, when the second size was selected in the layout,  
222 the total size satisfaction ( $W \times S_s$ ) equals 5 ( $10 \times 0.5$ ).

### 223 **Inclusion/exclusion soft constraint satisfaction (I/Es)**

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

### 231 **Genetic Algorithm (GA)**

232 GA is a heuristic optimization method based on biology used to search for near-optimum  
233 solutions. The site geometry, facility information, hard constraints and soft constraints are the  
234 inputs of GA. The first step in GA is to identify the variables and their searching space. Location,  
235 orientation and size are three attributes of the facilities to be optimized through GA. In GA, “genes”  
236 represent optimizing variables. A set of genes, namely a “chromosome,” composes one candidate  
237 solution. The composition of the chromosomes is shown in Figure 4 (a). As seen in this figure, the  
238 chromosome is conceptually divided into blocks of genes where each block is related to a facility,  
239 and  $n$  is the total number of facilities. Each block can have at most three genes allocated to location,  
240 orientation and size of that facility if they are variable. If they are not variable, the corresponding  
241 genes are eliminated. The searching domain for the location of the facilities is identified using the  
242 site geometry information and site hard constraints encoded by the cell number designated to the

243 facility. The searching domain for the orientation of facilities is 0 and 90 degree encoded by a  
244 binary number. For the size, the searching domain depends on the number of sizes defined by the  
245 planner for that facility encoded by the ordinal number (i.e., 1, 2, 3, etc.) assigned to each  
246 predefined size. Once the genes and their searching domains are specified using the input data, GA  
247 optimization is initiated following the steps shown in Figure 4b to maximize FI as a fitness  
248 function. In this process, three operations (i.e., selection, crossover, and mutation) are performed  
249 on the chromosomes to evolve from one generation to the next. In selection, two chromosomes are  
250 randomly selected for crossover while the fitter chromosomes (i.e., chromosomes with higher FI)  
251 have a higher chance of being selected. In crossover, some genes of the selected chromosomes are  
252 randomly swapped. For mutation, one or more genes are randomly selected and its value is altered  
253 to another value from its searching domain (see Mitchell (1999) for further information on GA  
254 operations).

255 The feasibility of the created chromosomes is also checked after crossover, mutation, and  
256 randomly generating the first generation. That is, all chromosomes (i.e., layouts) must satisfy the  
257 hard constraints. Performing these operations results in creating a new generation, and this process  
258 is iterated to reach the maximum number of generations. The population size (the number of  
259 chromosomes in each generation), the crossover and mutation rates (the probability of performing  
260 crossover and mutation on the selected chromosomes), and the maximum number of generations  
261 are the GA parameters that should be determined by the user. In most past studies, GA aims to  
262 find a single near-optimum solution. However, in this study, GA identifies a set of near-optimum  
263 solutions as elite layouts due to the fact that the optimum layout from the qualitative aspects is not  
264 necessarily the most cost efficient layout in practice. To this end, all the site layouts generated  
265 through GA are stored in a repository and ranked based on their FI values. At the end of

266 optimization, the planner can choose N number of the top ranked site layouts to be examined by  
267 simulation and forecast their cost efficiency. In fact, GA eliminates less qualified site layouts,  
268 which do not merit examination by simulation since running the simulation model for a large  
269 number of scenarios is costly and time consuming. Number N could be different in each problem  
270 depending on the variability of FI, sophistication of the simulation model for running different  
271 scenarios, and users' preferences. The recognized elite layouts are imported to CEP to evaluate  
272 their cost index, which is described in the next section.

### 273 **Cost Evaluation Phase (CEP)**

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

284 To build the simulation model, the elite layouts, the construction process information and the  
285 cost information are the inputs. The construction process information includes the information on  
286 construction activities (e.g., the durations, required resources and sequences of activities) and the  
287 construction planning decisions influencing the efficiency of the site layout (e.g., material delivery  
288 and logistic plans). For instance, in order to model material flow, diverse variables such as

289 construction production rate, facility size, distances between facilities, availability of the material  
290 handler resources, material delivery and/or removal plans, and the managerial actions to resolve  
291 space shortage may require modeling. That is, simulation can model existing dynamic and complex  
292 interactions between these parameters. Stochastic simulation can also suitably model uncertainties  
293 inherent in construction projects. To calculate CI of each layout, the total cost of the project for  
294 that layout is divided by the maximum cost of the project among all elite layouts.

### 295 **Value Evaluation Phase (VEP)**

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

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

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

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

302- modeling construction processes along with resources, uncertainties and dynamic interaction  
303 between different parameters, and quantifying the impact of facility location and size on the project  
304 using simulation in CEP,

305- considering facility size in the framework using Ss in calculating FI, which qualitatively models  
306 facility size preferences, and using simulation to quantitatively model the facility size impacts on  
307 the project costs, and

308- developing a new method (i.e., ds) to more realistically model closeness constraints

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



310 **Case Study**

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

332 Table 1 lists the required facilities, their type and size. It illustrates that the segment storage and

333 spoil pile are variable-size (and the planner has defined different sizes that could be assigned to  
334 them), while the other facilities have predetermined sizes.  $W$  and  $S_s$  for variable-size facilities are  
335 also given in Table 1. Since the planner would generally prefer to have larger storages on the site,  
336 higher  $S_s$  was assigned to the larger sizes. However, this preference could be compromised due to  
337 existence of other constraints, or high costs of having larger storage areas. The ability to consider  
338 variable facility size is another advantage of this framework over SWDF. Table 2 to Table 5 give  
339 the constraints defined for locating and sizing these facilities. It should be noted that some facilities  
340 (e.g., ventilation system, switch gear, construction box, and propane tank) are required on  
341 tunneling sites; however, their location and size do not have any impacts on the project cost, and  
342 their locations are constrained by the closeness constraints. That is, changes in the location of these  
343 facilities do not have any impacts on CI, and can only be evaluated by FI. For example, the distance  
344 between the propane tank and the site trailer does not impact CI. In this example,  $d_s$  between  
345 propane tank's center and the closest point of the site trailer was defined with three points: (0,1),  
346 (1,1) and (5,0), because of the fact that the propane tank should be connected to the trailer for its  
347 use. Therefore, the distance farther than 5 m is not desirable, and the satisfaction for the distance  
348 more than 5 meters is considered 0. SWDF cannot appropriately model this kind of constraints  
349 because its objective function linearly varies by distance. That is, FI can more realistically evaluate  
350 distance constraints than SWDF. In addition, inclusion/exclusion area soft constraints can be  
351 considered in FI. For instance, the preference of the planner is to locate the spoil pile in the  
352 specified loading area due to the fact that trucks can access to the spoil pile from Access Road 1  
353 more easily than Access Road 2, which interfaces South Gate Area. This preference was not a hard  
354 constraint for the planner, so it was modeled using the inclusion area soft constraint, which cannot  
355 be modeled by SWDF.

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

369 The preliminary construction planning decisions assumed in this study as Scenario #1 are:  
370 deploying a truck with a capacity of 5 m<sup>3</sup> for removing the soil from the site, and a segment  
371 delivery plan of 48 segments/week to the site. To demonstrate variation of the layouts' efficiency  
372 by changing these variables, two more scenarios are also considered: Scenario #2, in which a truck  
373 with a capacity of 6 m<sup>3</sup> is deployed, and Scenario #3, in which the segment delivery plan is 48  
374 segments per 8 days. Scenario #2 can reduce the delays caused by lack of space in the soil pile and  
375 improve the production rate, but incurs extra costs for deploying a larger truck. Scenario #3 can  
376 reduce the cost of off-site storage by delivering segments less frequently to the site, but can  
377 increase the risk of segment stock-out, since uncertainties of late segment delivery for 1 to 2 days  
378 were considered as 10% in the model. The impact of these changes on the project cost are evaluated

379 through simulation. GA parameters used in the model are 100, 200, 0.9, and 0.04 for population  
380 size, number of generations, crossover rate and mutation rate, respectively. Having run GA  
381 optimization in FEP, 35 layouts were selected as elite layouts to be imported into the simulation  
382 model, condensing the significance of the differences between the FI values. The simulation model  
383 was run 100 times for each elite layout in CEP. The optimum layout was the one shown in Figure  
384 5 (c) under Scenario #1 for construction planning decision. Note that the maximum cost from the  
385 three scenarios is considered when calculating CI.

### 386 **Result Analysis**

387 In this case study, GA produced different layouts of which FI varies from 0.36 to 0.88 with the  
388 average of 0.67. In CEP, only 35 layouts that could satisfy more than 85% of the soft constraints  
389 (i.e.,  $FI > 0.85$ ) were selected as elite layouts. The list of elite layouts with their FI, CI and VI values  
390 as well as the size of the spoil pile and segment storage, and their distance from the shaft are  
391 presented in Table 6. As seen in this table, the layout with the highest functionality does not have  
392 the lowest cost. The optimum layout is Layout #1 under Scenario #1, which has the highest FI but  
393 1.1% more costs than the least costs of the elite layouts. It is also seen that FI values of some  
394 layouts are the same, which is because the soft constraint satisfaction is not affected by changing  
395 the orientation of facilities from 0 to 90 degrees, or vice versa. Another reason is likely the soft  
396 constraints of inclusion/exclusion areas, which is satisfied by positioning a facility on any location  
397 inside/outside of the specified area. That is, several locations for a facility result in the same  
398 satisfaction value. This may also happen to some forms of the distance constraint satisfaction such  
399 as the ones shown in Figure 3 (a) and (b), which result in the same distance satisfaction value if  
400 the distance between the facilities is less than  $d_1$  and  $d_3$ , respectively. This can bring about a more  
401 realistic model since in real projects, slight changes in location and/or orientation of some facilities

402 may have insignificant impacts on the quality of the layout.

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

409 - Layout #1 as the optimum layout can be analyzed among the three construction planning scenarios.  
410 While using the larger truck could improve the production rate by reducing the probability of  
411 lacking space in the spoil pile and save some cost, the cost incurred by deploying the larger truck  
412 could balance this cost. So thus, CI values of Layout #1 for Scenario #1 is slightly less than that  
413 of Scenario #2. On the other hand, increasing segment delivery interval for only 1 day in Scenario  
414 #3 could significantly (i.e., about 6.7%) increase the cost of Layout #1. This is because of the fact  
415 that the cost lost by segment stock-out considerably exceeded the cost saved for using less off-site  
416 storage. Note that SWDF is not able to account for the impact of construction planning variables  
417 on the efficiency of the layout.

418 - Comparing Layout #1 and #16 shows that main differences between the layouts, which can impact  
419 the costs, are the location and size of the segment storage. Having a smaller size of the segment  
420 storage in Layout #16 led to less costs for the mobilization, demobilization and maintenance as  
421 well as less direct and indirect costs due to improving production rate by positioning it closer to  
422 the shaft. On the other hand, the smaller on-site storage exposes the project to extra cost for off-  
423 site storage. This extra cost can be reduced when the production rate is improved by positing the  
424 segment storage closer to the shaft (see Figure 5 (a) for further information). As a result of cost

425 analysis performed by simulation, Layout #16 has less (between 0.9% and 1.6%) costs than Layout  
426 #1 under the three scenarios; SWDF is not able to perform this detailed analysis on the cost impact  
427 of facility size and location.

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

448 calculated as 0.7977, which is 14.4% less than that of Layout #1. Hence, SWDF resulted in a less  
449 efficient layout than the proposed method.

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

### 463 **Verification and Validation of the Model**

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

### 467 **Conclusion**

468 This paper outlined a framework employing GA and simulation for decision making for site  
469 layout planning. The main contributions of this study are to:  
470 - develop a novel method to qualitatively evaluate the functionality of site layouts by modeling

471 distance constraints more realistically and considering the size and location preferences; and  
472 - forecast the cost efficiency of site layouts using simulation, which can more realistically quantify  
473 the mutual impacts of site layout and construction operation on the project costs by modeling  
474 complex construction processes, inherent uncertainties, utilized resources and dynamic  
475 interactions between different parameters.

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

#### 484 **Acknowledgement**

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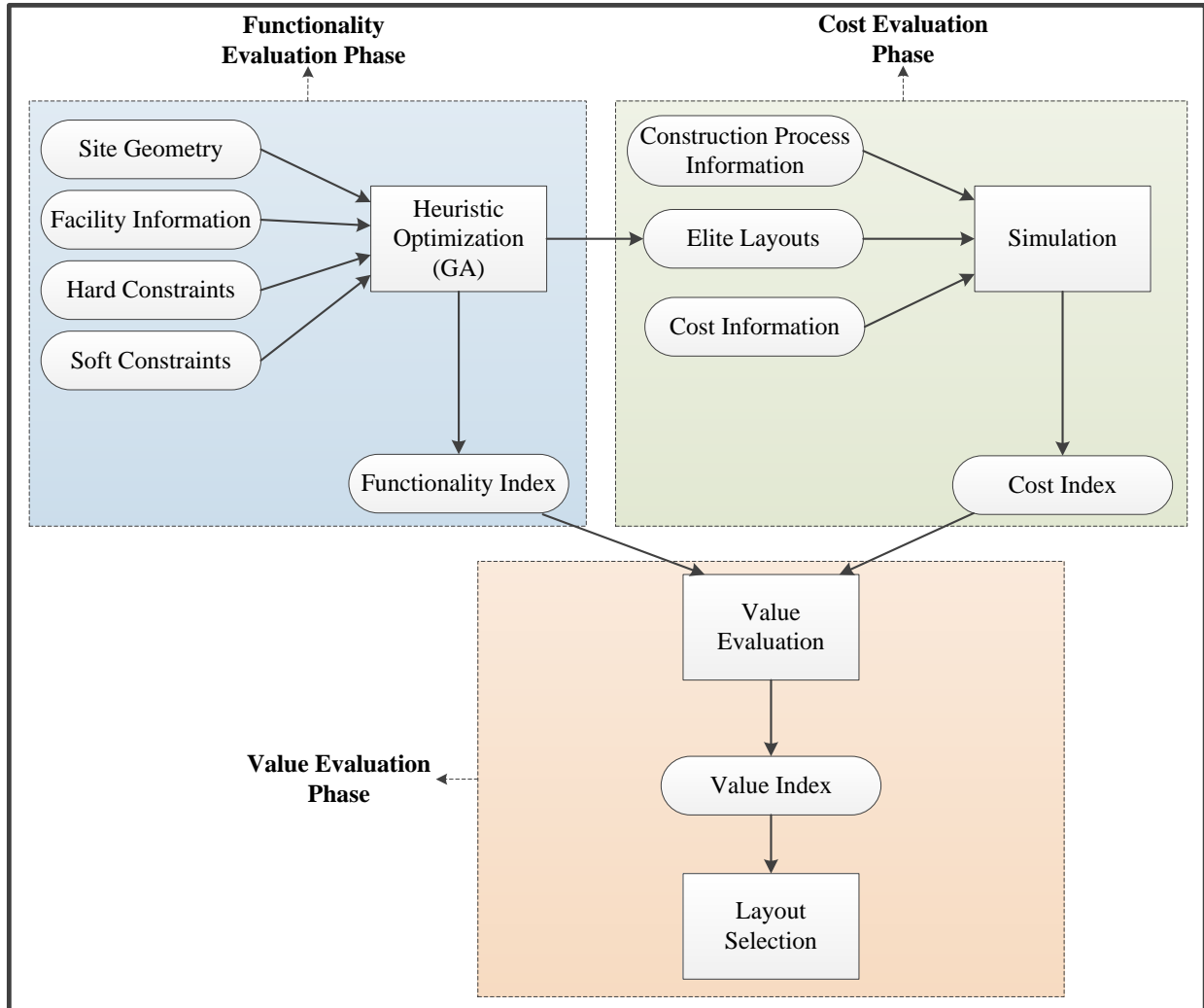
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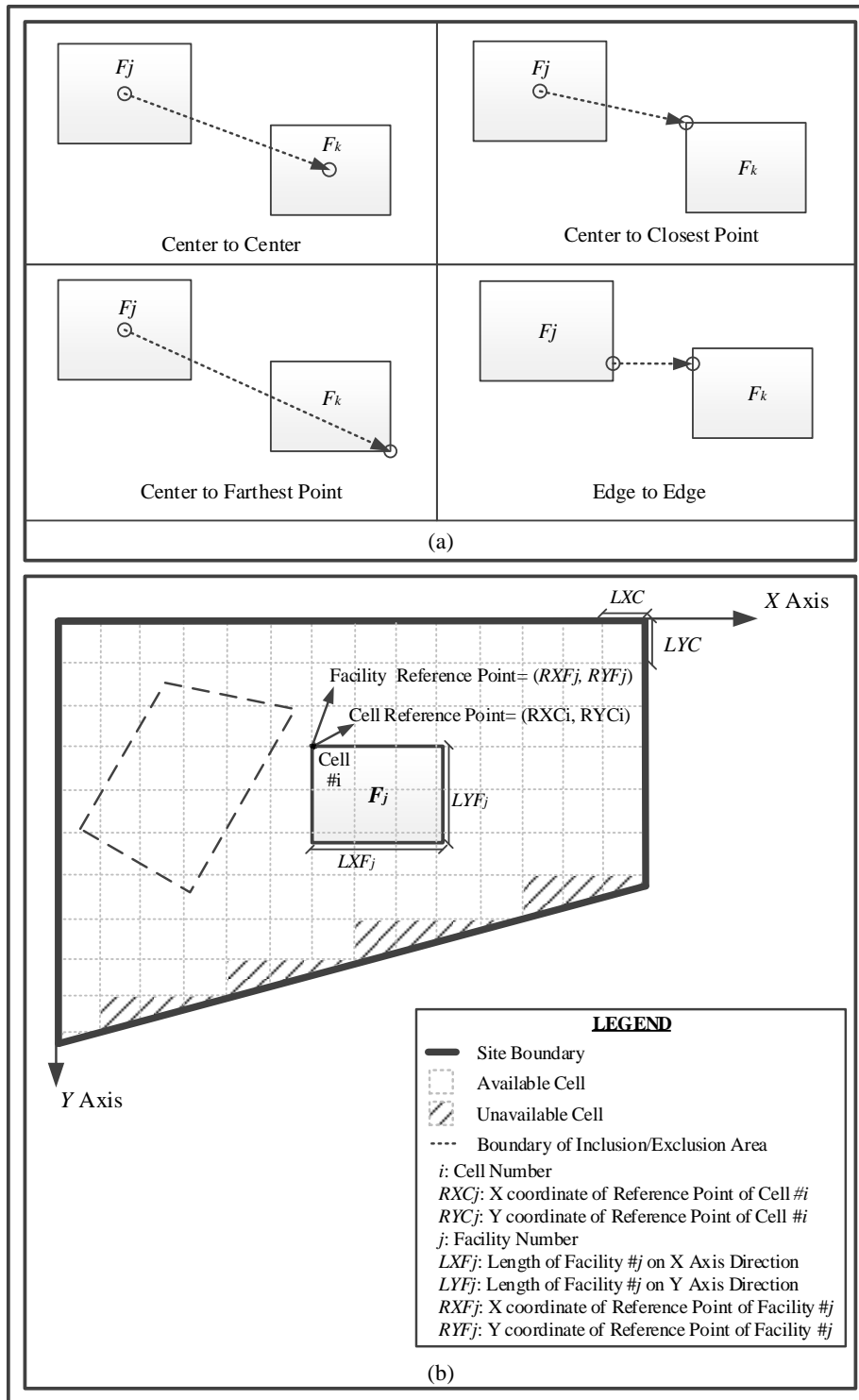
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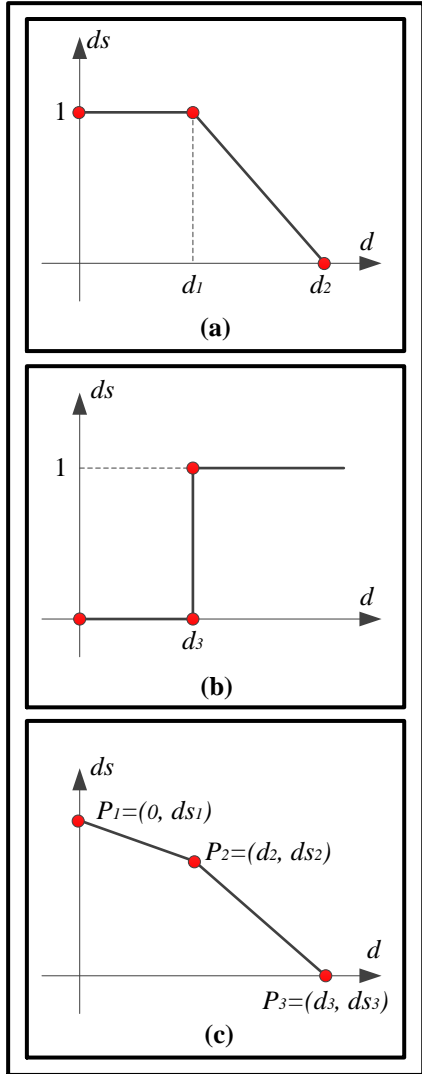
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527 Figure 1. Overview of the decision making framework



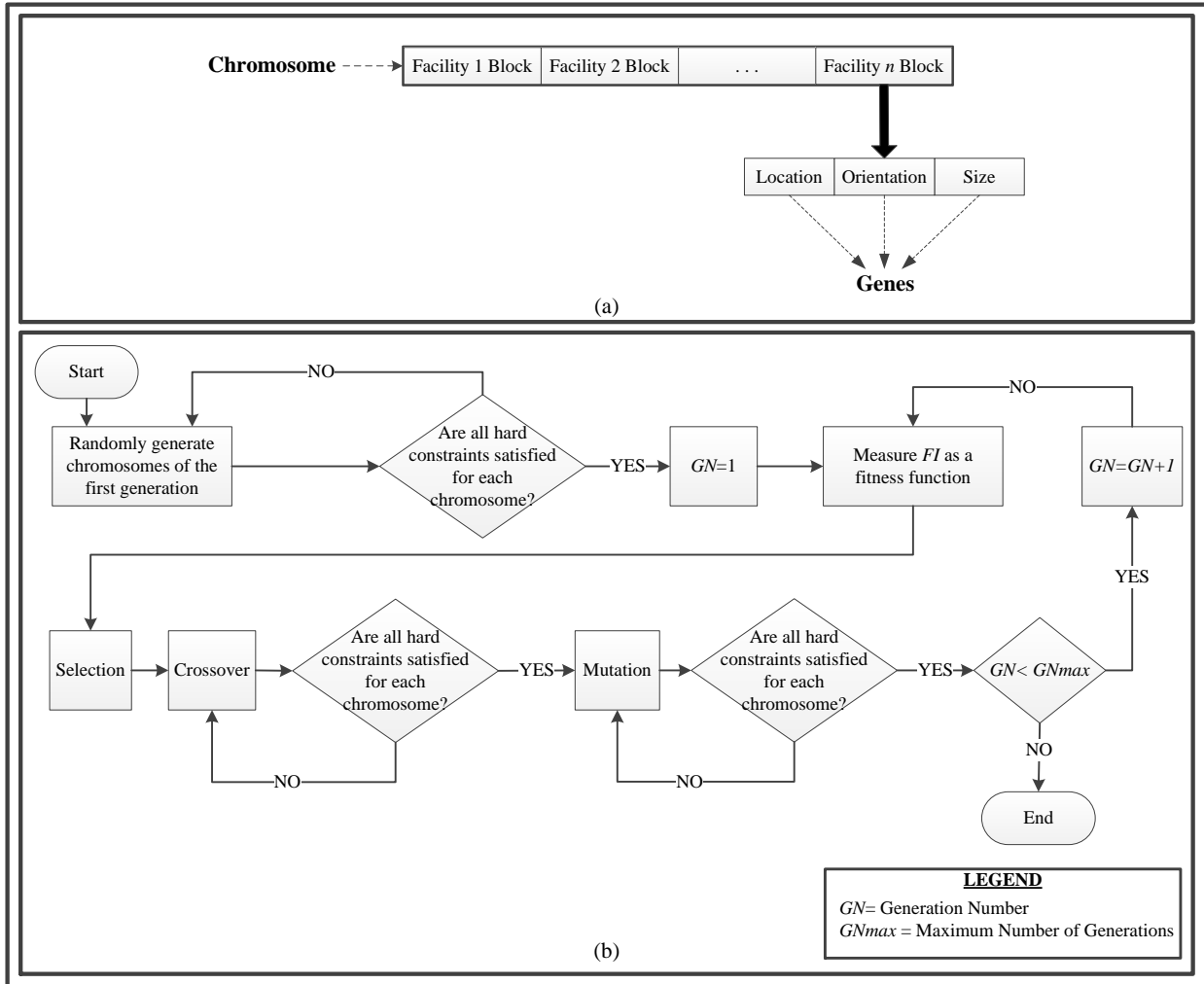
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529 Figure 2. (a) Schematic view of distance measurement types, and (b) site boundaries, gridlines,  
 530 facilities, and areas



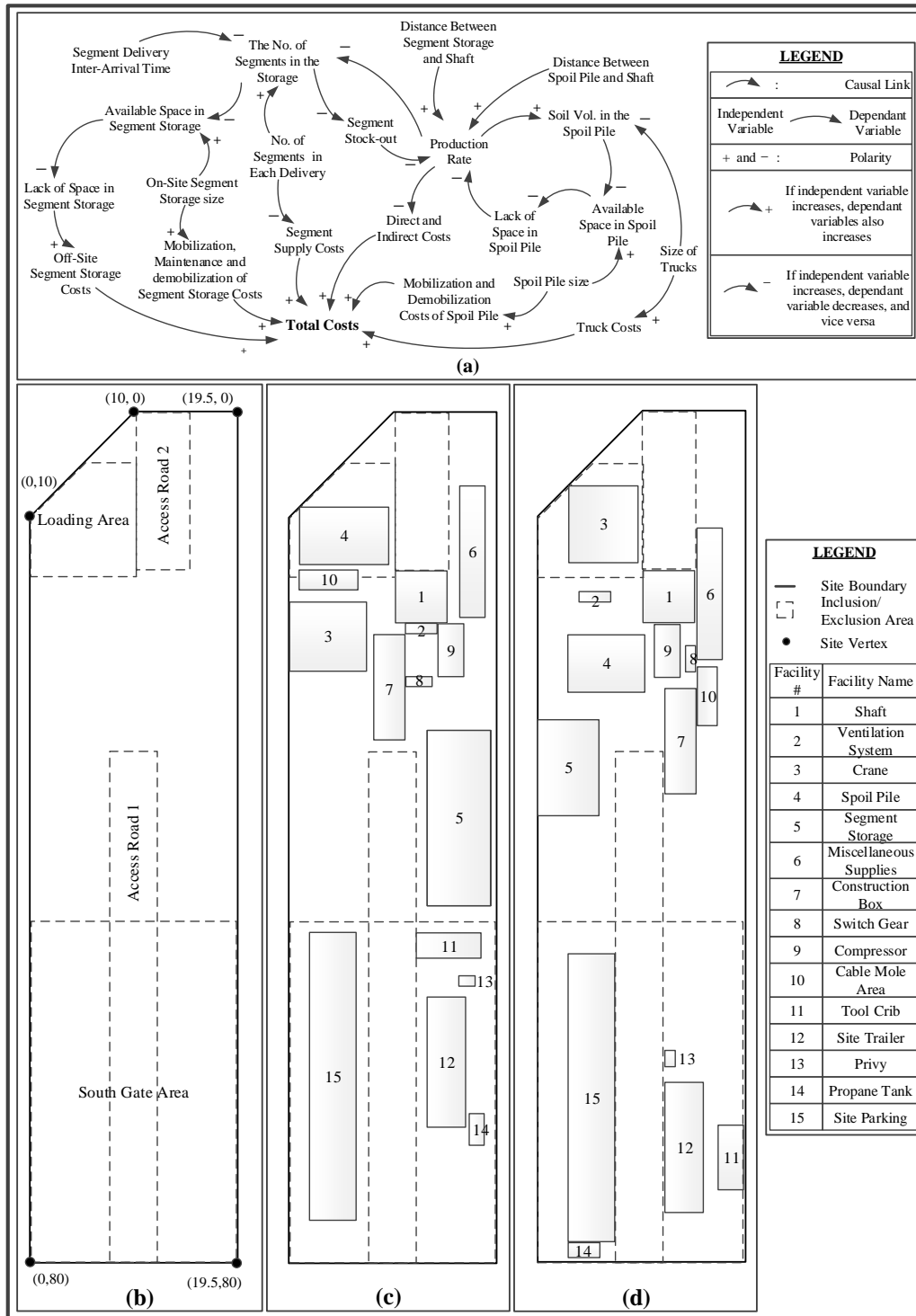
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532 Figure 3. The form of the distance constraint satisfaction



533

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



535

536 Figure 5 (a): Dependencies among variables in site layout planning of tunneling projects (b): site

537 overview, (c): optimum layout from the developed framework, and (d) optimum layout from

538 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) <sup>a</sup>	Fixed	Fixed	5×5/ NA	NA <sup>d</sup>	NA	NA
2	Crane	Variable	Variable	Fixed	6.6×7.3/ NA	NA	NA	NA
3	Spoil Pile	Variable	Variable	Variable (W=7) <sup>c</sup>	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) <sup>c</sup>	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) <sup>b</sup>	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) <sup>b</sup>	Fixed	4.4×27/ NA	NA	NA	NA
15	Ventilation	Variable	Variable	Fixed	1×3/ NA	NA	NA	NA

540 <sup>a</sup> Coordinates of the reference point if the facility is fixed-location

541 <sup>b</sup> Degree of rotation if the facility is fixed-orientation

542 <sup>c</sup> Weight of size satisfaction if facility is variable-size

543 <sup>d</sup> “Not Applicable”

544

545

Table 2. Distance hard constraints for positioning facilities

<b>Facility 1</b>	<b>Facility 2</b>	<b>Distance Type</b>	<b>D<sub>min</sub> (m)</b>	<b>D<sub>max</sub> (m)</b>
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

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

<b>Area Name</b>	<b>Facility Name</b>	<b>Inclusion/ Exclusion</b>	<b>Coordinates of Area Vertices</b>
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)

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Table 4. Distance soft constraints for positioning facilities

<b>First Facility</b>	<b>Second Facility</b>	<b>Distance Type</b>	<b>Weight</b>	<b>Ds (Coordinates of Three Points)</b>
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)

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

<b>Area Name</b>	<b>Facility Name</b>	<b>Inclusion/ Exclusion</b>	<b>Weight</b>	<b>Coordinates of Area Vertices</b>
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)

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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 <sup>a</sup>	0.9442	0.9325 <sup>c</sup>	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 <sup>b</sup>	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

559 <sup>a</sup> Highest FI

560 <sup>b</sup>Lowest CI  
561 <sup>c</sup>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.