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1 **A Hybrid Simulation Approach for Quantitatively Analyzing the Impact of Facility Size on**
2 **Construction Projects**

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17 **Abstract**

18 Sizing temporary facilities is a crucial task in construction site layout planning due to its
19 significant impact on project productivity and cost. This paper describes a simulation-based
20 approach for modeling the size of facilities that temporarily contain materials in construction
21 projects. Different methods have been introduced for estimating the required size of this kind of
22 facility; however, space limitations, particularly on congested sites, may not allow the planner to
23 allocate the estimated space to the facilities. This study aims at quantitatively analysing the
24 impact of facility size on the project and modeling the managerial corrective actions to remedy
25 the space shortage in facilities. To this end, a hybrid discrete-continuous simulation technique is
26 adopted. Simulation is superior in modeling dynamic interactions between variables as well as
27 modeling construction processes with inherent uncertainties. The combination of discrete and
28 continuous simulation is used to enhance accuracy and model the project at both operational
29 level (i.e. activity level with higher level of detail) to estimate production rate, and strategic level
30 (i.e. macro level with lower level of detail) to account for some construction planning decisions
31 such as material management variables. The novelty of this study is analyzing the impact of

32 facility size on the project time and cost, while managerial actions taken to resolve space
33 shortages are modeled, and interdependent influencing parameters of the different disciplines,
34 such as site layout, material management, logistics and construction process planning are
35 integrated in a unified model. The applicability and suitability of the proposed approach is
36 demonstrated in layout planning of a tunneling project site.

37 **Key words:** *site layout planning, simulation, hybrid discrete-continuous simulation, sizing*
38 *temporary facilities, material management, construction planning.*

39 **Introduction**

40 Identifying the size of temporary facilities is a crucial task in the site layout planning
41 stage of construction projects. While size of some facilities (e.g. batch plants and equipment) is
42 predetermined and fixed, size of other facilities (e.g. material laydowns and stock piles) is
43 variable and should be determined in this stage. In construction projects, variable-size facilities
44 are mostly related to facilities temporarily containing materials. Hence, they can be referred to as
45 “material-dependant facilities.” This study focuses on modeling the size of material-dependant
46 facilities due to its significant impacts on project productivity and cost.

47 Facilities occupy space on sites. Space is an important resource in construction projects
48 (Hegazy and Elbeltagi, 1999), so this resource should be used efficiently through optimum
49 facility size planning. On small sites, sizing facilities is more critical because of limitations on
50 the space and the consequences of inaccurate estimation of facility size. In general, improperly
51 sizing facilities imposes congestion and space conflicts, which adversely influences the
52 productivity and safety of projects (Halligan et al., 1994; Akinci et al., 1998; Winch and North,
53 2006). Specifically, underestimation of the size of material-dependant facilities causes space
54 shortage for that facility, which can result in loss of productivity, and incur extra cost for

55 resolving the encountered problems. For example, insufficient size allocation of a material
56 storage can cause lower productivity in many ways, such as: interrupting material flow when
57 there is no space for offloading materials, and spending more time on finding and handling
58 materials when the storage is congested. On small sites, however, insufficient space for material-
59 dependant facilities may be unavoidable, and in these cases, the planner should alter some
60 construction planning decisions (e.g. material delivery plan) to reduce the need for space on the
61 site. As such, considering those variables as well as the corrective actions to resolve space
62 shortages is vital in modeling facility size. On the other hand, overestimation of facility size can
63 impose spatial conflicts and lack of space for the other facilities. On large sites where space is
64 not limited, facility installation and maintenance costs are the drivers of facility size. As an
65 objective of this research, the impacts of material-dependant facility size on different aspects of a
66 project such as productivity, material flow, size of other facilities and project cost and time are
67 quantitatively evaluated.

68 Although sizing facilities is considered a part of site layout planning tasks (Tommelein,
69 1992), most studies in construction site layout planning focused on optimizing the position of the
70 facilities (e.g. Ning, et al. (2010), Ning, et al. (2011), and Xu & Li (2012)), and less attention
71 was paid to efficiently planning the size of the facilities. In the context of site layout planning,
72 Elbeltagi and Hegazy (2001) proposed a knowledge-based method to identify required areas of a
73 number of temporary facilities using IF-THEN rules. The implemented rules were defined on the
74 basis of personnel requirements, estimated quantity of work, production rate of resources,
75 availability of site space, and cost, but did not account for possible variation of these parameters
76 throughout the project. In space scheduling, Zouein and Tommelein (2001) categorized the
77 profile of the space needs for facilities into resource independent, which was fixed, and resource
78 dependant which was either fixed or variable over the project. For the variable profiles, space

79 needs might decrease linearly or fluctuate between minimum and maximum levels as the
80 corresponding activities progress, which are over-simplified assumptions. The size of the
81 facilities is also addressed in the unequal-area facility layout problems (e.g. studies by Zhang &
82 Wang, (2008) and Li & Love (2000)), in which facilities are assigned to predetermined locations,
83 and due to the size constraints, large facilities cannot be assigned to small size locations.
84 Although the size of the facilities is considered in this assignment, this approach cannot
85 quantitatively assess the impact of the facility size on the project time or cost.

86 Facility size and required space for facilities were noted in other contexts, such as time-
87 space conflict analysis (Akinici et al., 2002), integration of schedule and space planning (Zouein
88 and Shedid, 2002), and workspace management (Chavada et al., 2012). In these studies, the
89 influence of spatial conflicts and the methods to manage them were discussed; however, the
90 sizing of facilities was not presented.

91 In one of the most recent studies, Said and El-Rayes (2011) developed a model for
92 optimizing material procurement decision variables and material storage layout to achieve
93 minimum logistics costs. In their model, material demand rates and material procurement
94 decision variables influence the required size of the material storage area determined
95 heuristically. Despite the novelty of this study, the uncertainties in construction projects could
96 have been taken into account for estimating the material demand rate, which was based on a
97 certain construction plan in the model.

98 For modeling dynamics and uncertainties inherent in construction projects, simulation
99 has often been utilized in the literature (e.g. Tang et al. (2013) and Said et al. (2009)). In relevant
100 research, Ebrahimi et al. (2011) used simulation to model supply chain management in tunneling
101 construction, and evaluated the effect of space shortage for storing concrete segment liners,
102 located on supplier's sites and the construction site, on the project time. This research

103 demonstrated the capability of simulation to model storage capacity and the effect of space
104 shortage on the project time. Alanjari et al. (2014) integrated simulation with genetic algorithm
105 to optimize material placement layout in yard laydowns. RazaviAlavi et al. (2014) also used a
106 simulation-based approach to more accurately model variation of the space required for facilities
107 throughout construction projects. However, these studies overlooked the site layout constraints in
108 sizing facilities, and could not model the situation in which the required space for facilities is not
109 available on the site. Cellular automata (CA) is another technique that can be used for modeling
110 space represented by uniform grids. Zhang et al. (2007) used CA to model space resources in
111 construction simulation, analyze spatial conflicts, and visualize the occupied space on
112 construction sites. Agent-based simulation can also be used to model some features in layout
113 planning such as workers' movements. Said et al. (2012) used agent-based simulation to evaluate
114 performance of labor emergency evacuation plans considering geometry of the site.

115 Managerial corrective actions taken to remedy encountered problems need to be modeled
116 to represent real-world projects (Lee et al., 2009). This issue is essential in layout planning on
117 congested sites because the planners may not be able to provide the required space for all
118 facilities. Consequently, they may shrink the size of some facilities and take managerial actions
119 when lacking space on the site. According to the main objective of this research, a simulation-
120 based approach is adopted to quantitatively analyze the impact of size of material-dependant
121 facilities on the project time and cost, model managerial actions and dynamic interactions
122 between the interdependent variables, and consider uncertainties in construction projects. A
123 combination of discrete event simulation (DES) and continuous simulation (CS) is used for more
124 accurately modeling material flow and managerial actions. The proposed approach also aims to
125 consider site layout constraints, and planning decisions of different disciplines, such as
126 construction operation planning, material management and logistics, in a unified model.

127 The following sections describe the research methodology and the approach for modeling
128 facility size and managerial actions. Next, a case study is presented to demonstrate
129 implementation of the developed approach. In the last section, the paper is summarized and the
130 conclusion is drawn.

131 **Research Methodology**

132 For sizing material-dependant facilities, the amount of material placed within a facility
133 should be accounted for throughout the project time. To this end, material flow should be
134 modeled to identify the quantity of material and time that materials come into the facility and
135 leave the facility (i.e. material inflow to the facility and outflow from the facility). Although it is
136 difficult to introduce a generic model for material flow in construction projects, the production of
137 the system is always part of the model. To outline the significance of the system production,
138 material-dependant facilities on the construction sites are categorized into three groups:

- 139 • Group I: For this group, only the material inflow of the facility comes from the system
140 production, which is very common in earthmoving projects. For instance, a spoil pile can
141 be classified as Group I where its inflow is produced from the excavation executed in the
142 construction process. Then, the soil may be hauled from the site by trucks to an off-site
143 dumping area.
- 144 • Group II: For this group, only the material outflow of the facility is to be consumed in the
145 production process of the system, which is very common when the material is delivered
146 to the site and consumed throughout the project. In steel structure projects, for example,
147 steel materials are purchased from a supplier and stacked on the site to be erected in the
148 project, so the steel material storage can be considered Group II.
- 149 • Group III: For this group, the material inflow comes from the system production and the

150 material outflow goes to be consumed in the production of the same system or another
151 system. For instance, the intermediate storage containing modules produced in the
152 module yard and going to be installed on construction sites can be categorized as Group
153 III. In this example, the material inflow comes from the production of the module yard,
154 and material outflow goes to the production of the construction site. An example of the
155 same production system for both inflow and outflow is the temporary soil stockpile
156 maintaining the soil excavated in pipeline construction to be used in filling of the
157 excavation after installing the pipes.

158 As a result of this classification, the accuracy of the production rate estimate is identified
159 as a key component in accurately sizing any material-dependant facilities. In addition, the
160 quantity of available material in a facility can influence the production. For instance, when the
161 material storage is stock-out, or its capacity is full, it can interrupt the production rate. This
162 mutual effect, which is mostly oversight in the existing methods, is important to be modeled. In
163 construction projects, estimating production rate is a complicated process due to the dynamic
164 nature of construction, and complexity of construction operations. In particular, the construction
165 uncertainties cause production rate variations, which make it difficult to capture the interaction
166 between production rate and other variables like material flow and facility size. To overcome
167 these challenges, simulation is used to model material flow, production rate, and their dynamic
168 interactions due to superiorities of simulation in capturing dynamics of construction, and
169 considering construction uncertainties using stochastic input data.

170 For modeling material flow, different perspectives exist. Materials are naturally either
171 continuous (e.g. soil, cement, concrete and oil) or discrete (e.g. precast concrete panels, steel
172 pieces and bricks). However, the flow of continuous materials can be modeled discretely if the

173 materials' containers, such as a bucket of soil and a tanker of oil, are considered. The flow of
174 discrete materials can also be modeled continuously if the materials are aggregated. Considering
175 this fact, either discrete event simulation, continuous simulation or combined discrete-continuous
176 simulation can be utilized to model material flow.

177 In discrete event simulation (DES), the system state is instantaneously changed (Roth,
178 1987), and the changes of the system state occur at event times, while it remains constant
179 between event times (Pritsker and O'Reilly, 1999). DES is more suitable for modeling
180 construction operations such as earthmoving and tunneling (Lee et al. 2007). Modeling at the
181 operational level (i.e. activity level), where DES is capable of modeling repetitive activities as
182 well as resources and their interactions, is important particularly for estimating production rate of
183 construction operations, which are commonly repetitive in nature.

184 In continuous simulation (CS), the state of the system is changed continuously (Roth,
185 1987), and it relies on the differential equation for determining the values of continuous
186 variables, as in Equation 1 (Pritsker and O'Reilly, 1999):

$$S(t_2) = S(t_1) + \frac{ds}{dt} dt \quad (1)$$

187 where $S(t_2)$ and $S(t_1)$ are the value of the continuous variable S at time t_2 and t_1 , respectively
188 ($t_2 = t_1 + dt$), and ds/dt is change rate of the continuous variable. CS is more suitable to model
189 at the strategic level with aggregated data (e.g. macroscopic models of supply chain (Pierreval, et
190 al., 2007)), where lower level of details and less modeling efforts than DES are needed (Reggelin
191 & Tolujew, 2011). CS is mostly used to predict the long-term behavior of the project and model
192 managerial corrective actions.

193 In combined DES-CS, however, both discrete and continuous changes are made to the
194 system state (Roth, 1987). This approach can model a system at both operational and strategic
195 level.

196 When adopting CS for modeling material flow, the available material within a facility can
197 be calculated using Equation (2), which implies that available material within the facility at time
198 t_2 equals the available material at time t_1 plus the differences of material inflow and outflow,
199 where $t_2 = t_1 + dt$.

$$\begin{aligned} & \text{Available material}(t_2) \\ &= \text{Available material}(t_1) + \frac{d(\text{Material inflow} - \text{Material outflow})}{dt} \times dt \end{aligned} \quad (2)$$

200 Continuous world view can enhance more accuracy in modeling material within facilities
201 particularly when lower level of the details is available. The following cases exhibit the
202 advantages of CS in modeling material flow.

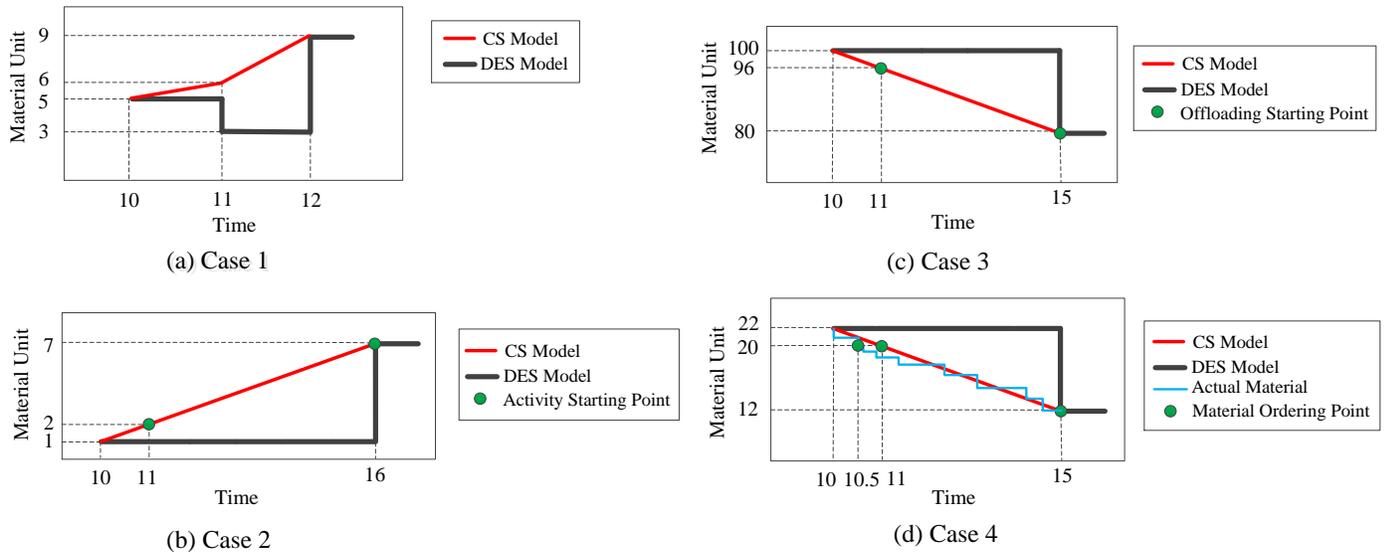
203 • Case 1 (when material inflow and outflow happen simultaneously): assume that at time
204 10, 5 units of material are available in the facility. At this time, 6 units of the material
205 come into a facility with the rate of 3 units of material per unit of time. At the same
206 time, 2 units of material are going out of the facility with the rate of 2 units of material
207 per unit of time. Comparing the result of discrete and continuous models for the
208 quantity of available material over time depicted in Figure 1 (a), it is seen that the
209 continuous model is more accurate, although the final result is the same.

210 • Case 2 (when there are not enough material units to start an activity): assume that there
211 is only one unit of material in stock at time 10 and an activity which needs 2 units of
212 material to start is waiting for delivery of the material. At this time, a batch of material
213 including 6 units with the rate of 1 unit of material per unit of time is coming to the

214 stock. In the DES model, the activity cannot start until all the units have been
215 offloaded, at time 16; however, in the CS model, the activity starts as soon as 2 units
216 are available, at time 11, as shown in Figure 1 (b).

217 • Case 3 (when there is not sufficient space for incoming material): assume that the
218 capacity of a facility is 100 units of material and it is full. An incoming batch including
219 4 units of the material is waiting for a space to be offloaded at time 10. At the same
220 time, 20 units of the material are going out of the facility with the rate of 4 units of
221 material per unit of time. As shown in Figure 1 (c), in the DES model, the incoming
222 batch cannot be offloaded until the whole 20 units leave the facility at time 15, while in
223 the CS model it is possible to offload it at time 11, which is more accurate.

224 • Case 4 (taking managerial actions when material level is reaching a threshold): DES is
225 a less reliable tool to model managerial actions because of its inconsistent time step size
226 (Lee et al., 2007). Assume that the strategy of a manager is to order material when the
227 available material units in the stock are less than 20 units. At time 10, the available
228 material is at 22, and at the same time, 10 units of material are going out of the stock
229 with the rate of 2 units of material per unit of time. In the CS model, the material order
230 is placed at time 11, while in the DES model, it is placed at time 15, which can increase
231 the risk of occurring stock-out, as depicted in Figure 1 (d).



232
233

Figure 1: CS versus DES for four example cases

234 These cases show that CS can be a more accurate tool for modeling material within
 235 facilities. It should be noted that the actual material flow may vary from the outputs of the CS
 236 model, particularly when discrete materials are modeled. As seen in Case 4 for instance, the
 237 actual time for material ordering is 10.5 while it is 11 in the CS model. Achieving this actual
 238 time in the model is possible only by having the detailed information for the flow of each
 239 material unit. However, considering the lower level of details available in the preplanning stage
 240 of projects on construction planning decisions such as material delivery schedules and material
 241 removal plans, CS is identified as a more realistic tool than DES at the strategic level (i.e. macro
 242 level). As discussed earlier, the DES model is more suitable than CS for modeling construction
 243 operations and estimating the production rate, which is crucial for sizing material-dependant
 244 facilities. As a result, the hybrid DES-CS simulation approach is implemented in this study to
 245 model material flow at both operational and strategic levels. In DES-CS models, three
 246 fundamental interactions exist between the changes occurring discretely and continuously in
 247 variables (Pritsker and O'Reilly 1999):

- 248 1. “A discrete change in value may be made to a continuous variable.”
- 249 2. “An event involving a continuous state variable achieving a threshold value may cause an
- 250 event to occur or to be scheduled.”
- 251 3. “The function description of continuous variables may be changed at discrete time
- 252 instants.”

253 These interactions are further discussed in the “Case Study” section.

254 **Modeling Facility Size Underlying Material Flow**

255 Decisions on the size of material-dependant facilities can be made directly on the basis of

256 the estimated quantity of the available material placed inside the facility. To this end, the

257 quantity of material, the occupied space/area, and the facility size (capacity) should be measured

258 by a unique unit, which depends on the type of the material and what is convenient for the

259 modellers. After measuring available material and facility size by a unique unit, the next step is

260 to calculate other relevant parameters (e.g. available space and fullness ratio of the facility) to

261 these variables, required for different modeling purposes like modeling managerial actions.

262 These parameters are considered continuous variables in the model because they are related to

263 another continuous variable: available material within a facility. That is, the changes of these

264 variables also occur continuously. If the facility size changes over time, it should also be defined

265 as a continuous variable. Utilizing Equation 1, facility size is computed, as in Equation 3:

$$\text{Facility size}(t_2) = \text{Facility size}(t_1) + \frac{d(\text{Facility size})}{dt} \times dt \quad (3)$$

266 where facility size(t_2) and facility size(t_1) are the values of facility size at times t_2 and t_1 ,

267 respectively, and $d(\text{Facility size})/dt$ is the rate of changing facility size ($t_2=t_1+dt$). Then, utilizing

268 Equation 1, the parameters of available space and fullness ratio of facilities are computed as in
 269 Equations 4 and 5, respectively.

$$\text{Available space}(t_2) = \text{Available space}(t_1) + \frac{d(\text{Available space})}{dt} \times dt \quad (4)$$

$$\text{Fullness ratio}(t_2) = \text{Fullness ratio}(t_1) + \frac{d(\text{Fullness ratio})}{dt} \times dt \quad (5)$$

270 According to definitions of available space (Equation 6) and fullness ratio (Equation 9), as
 271 well as Equations 2 and 3, the change rate of available space and fullness ratio can be calculated.
 272 The calculations for the available space are as follows:

$$\text{Available space} = \text{Facility size} - \text{Available material} \quad (6)$$

Derivative of Equation 6 is computed as Equations 7 and 8:

$$\frac{d(\text{Available space})}{dt} = \frac{d(\text{Facility size} - \text{Available material})}{dt} \quad (7)$$

$$\frac{d(\text{Available space})}{dt} = \frac{d(\text{Facility size})}{dt} - \frac{d(\text{Available material})}{dt} \quad (8)$$

273 For the Fullness ratio, the derivative of Equation 9 is computed as Equations 10 and 11.

$$\text{Fullness ratio} = \frac{\text{Available material}}{\text{Facility size}} \quad (9)$$

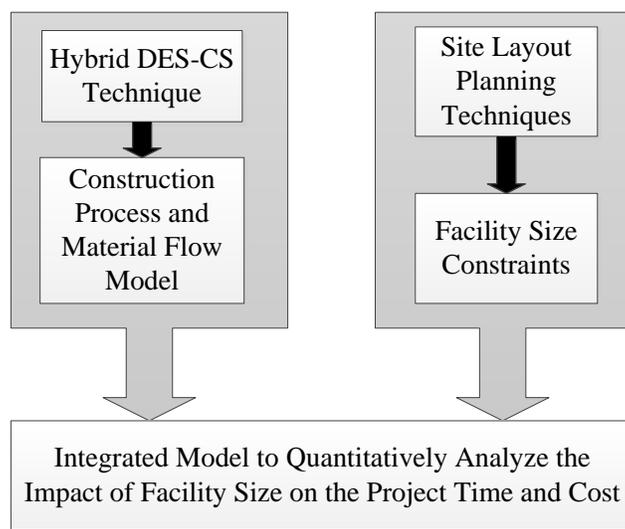
$$\frac{d(\text{Fullness ratio})}{dt} = \frac{d\left(\frac{\text{Available material}}{\text{Facility size}}\right)}{dt} \quad (10)$$

$$\frac{d(\text{Fullness ratio})}{dt} = \frac{\frac{d(\text{Available material})}{dt}}{\text{Facility size}(t_1)} - \frac{\text{Available material}(t_1)}{\text{Facility size}^2(t_1)} \times \frac{d(\text{Facility size})}{dt} \quad (11)$$

274 In these formulas, it is evident that if the facility size does not change, the term $d(\text{facility}$
 275 $\text{size})/dt$ equals zero, and $\text{Facility size}(t_1)$ has a constant value. Replacing Equations 8 and 11 in
 276 Equations 4 and 5, respectively, the value of available space and fullness ratio can be computed.

277 The same procedure could be followed to compute the other continuous variables. The examples
278 of these parameters' applications are further illustrated in the "Case Study" section.

279 In summary, as depicted in Figure 2, the integrated model created in this study employs
280 the hybrid DES-CS simulation to model material flow and facility size, which is determined
281 based on spatial constraints through site layout planning. This model will be able to
282 quantitatively analyze the impact of facility size on the project time and cost.



283

284

Figure 2: Adopted techniques to build the integrated model

285 **Modeling Managerial corrective Actions**

286 Managerial corrective actions are mostly disregarded when modeling real-world projects
287 by traditional construction simulation methods (Lee et al., 2009). As discussed earlier, the
288 combined discrete-continuous simulation method facilitates enhancing accuracy in modeling
289 managerial actions. This study mainly concentrates on the managerial actions for resolving space
290 shortage problems; however, there is no barrier to model the actions for other matters. Changing
291 facility size is one of the managerial actions taken when lacking space. Altering planning

292 decisions and changing material inflow and outflow are other managerial actions that can
293 influence the available material, and subsequently, reduce the demand for space within a facility.
294 These planning decisions may be pertinent to construction process planning (e.g. altering
295 working shift hours to change the system production rate), material management (e.g. altering
296 material procurement plan to change delivered material rate to the site), or logistics (e.g. altering
297 the number of material handlers to change material flow rate on the site).

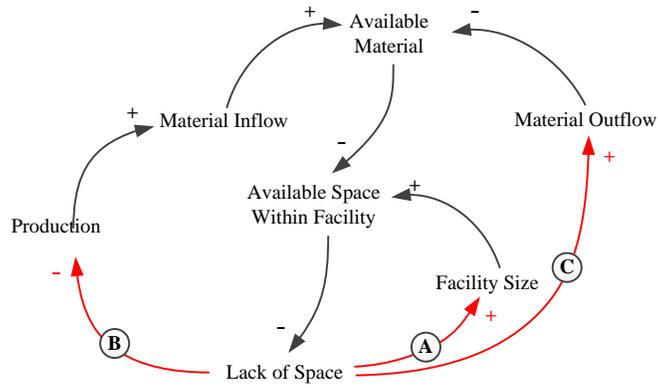
298 To exhibit general managerial actions when lacking space, and their influences on
299 projects, the three groups of material-dependant facilities, and their possible managerial actions
300 are presented adopting a “causal loop diagram” (Sterman, 2000). In this diagram, arrows, called
301 “causal links,” connect variables to denote the causal influence among variables; polarities,
302 either positive (+), or negative (-) assigned to causal links, indicate how independent variable
303 changes influence the dependant variable, where positive links mean if independent variables
304 increase, dependant variables also increase, and negative links mean if independent variables
305 increase, dependant variables decrease (Sterman, 2000). Figure 3 (a) shows the managerial
306 actions for Group I, for which the material inflow comes from the production of the system. For
307 Group I, increasing the production increases the material inflow and subsequently increases
308 available material, and reduces the available space within the facility. In consequence, system
309 production can cause lack of space, as illustrated in Figure 3 (a). Additionally, increasing facility
310 size increases available space within the facility, which reduces lack of space. It is noteworthy
311 that increasing the size of facilities may be executed by increasing size of the existing facility or
312 providing an additional facility to maintain that material. Material outflow is another variable
313 that influences the available material and space in the facility. Therefore, increasing material
314 outflow also reduces lack of space. As a result, production, facility size, and material outflow are

315 identified as the main variables influencing lack of space for Group I. To remedy lack of space,
316 three managerial actions can be taken:

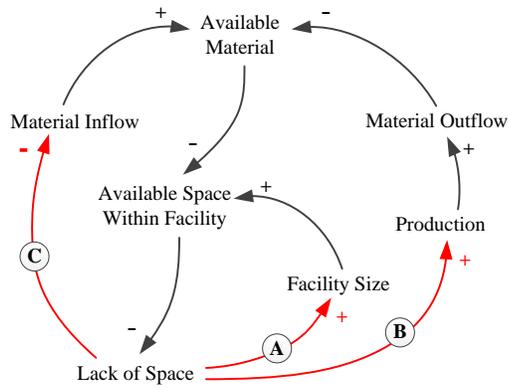
- 317 • Action A: increasing facility size.
- 318 • Action B: reducing system production rate (e.g. reducing working shift hours, reducing
319 employed resources, or even halting the production).
- 320 • Action C: increasing material outflow rate (e.g. employing more resources removing
321 materials from the facility).

322 Similarly, three managerial actions can be taken for Group II and III as shown in Figure 3
323 (b) and (c), respectively. As discussed earlier for Group III and seen in Figure 3 (c), Production
324 (I) and (II) are the production rates of two systems which could be the same in some cases. The
325 interdependency between variables highlights the significance of simulation models to capture
326 the impacts of the managerial actions on projects.

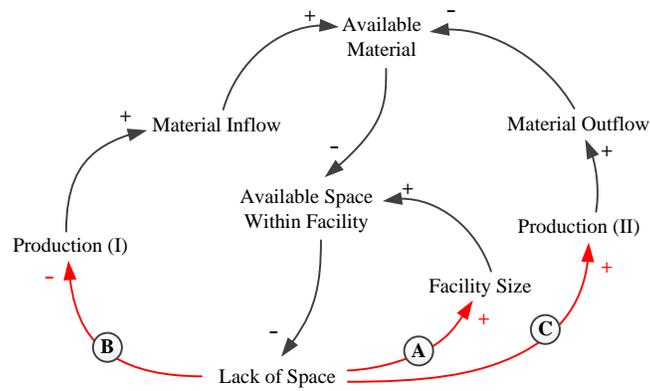
327 In the next section, a case study demonstrates the capabilities of simulation in modeling these
328 complex processes.



(a) Group I



(b) Group II



(c) Group III

329

330

Figure 3: Managerial actions for three groups

331

332 Case Study

333 To exhibit implementation of the proposed approach, layout planning of a tunneling
334 project is studied. In tunneling projects, the flow of two materials, including excavated soil
335 material, referred to as soil in this paper, and segments (i.e. concrete liners), exists throughout
336 most of the project time. Typically in Tunnel Boring Machine (TBM) tunneling, with the
337 existence of a working shaft to access the tunnel, once the TBM starts excavation, it fills muck
338 cars of a train and the train transfers soil from the tunnel face to the tunnel tail. At the tunnel tail,
339 a crane hoists the cars from the shaft to ground level and dumps the soil into a spoil pile. The
340 spoil pile temporarily maintains the soil that is later removed from the site by trucks. Figure 4 (a)
341 displays a flowchart of this process.

342 The segment flow is different, as depicted in Figure 4 (b). The segments are delivered
343 from a supplier to the site, and offloaded in the segment storage area. Then, when needed, the
344 segments are taken from storage using the crane to place them into cars. The cars transport the
345 segments from the tunnel tail to the tunnel face. Finally, they are installed by the TBM.
346 According to the described material flows, the spoil pile and the segment storage are categorized
347 as Group (I) and Group (II) of the material-dependent facilities, respectively. In addition to
348 activities involved in material flow, the other activities corresponding to tunneling should be
349 considered to model the construction process. These activities include resetting the TBM,
350 surveying, and rail track extensions (see Ruwanpura et al. (2001) for further information on the
351 tunneling process). Due to uncertainties in the tunneling construction process, particularly the
352 geotechnical parameters of the soil, as well as the segment supply and productivity of the soil
353 removal, some input data such as the TBM penetration rate, the segment inflow and soil outflow
354 rates, and the duration of most activities are considered stochastically in the simulation model.
355 Table 1 gives information on the main characteristics of the case study. In the simulation model

356 built in the Symphony environment (Hajjar and AbouRizk, 1996), Symphony.NET 4.0 version,
 357 the tunneling tasks at the operational level are modeled by DES as resource interactions are
 358 important for estimating tunneling production rate. The segment supply and the soil removal are
 359 modeled by CS at the strategic level, since a high level of detail (e.g. the precise information on
 360 the segment delivery time, truck availability time on the site for loading the soil, and the truck
 361 cycle time for dumping the soil on the dump site) is not available at the preplanning phase.
 362 Figure 4 also shows the utilized approaches in modeling different parts of the soil and segment
 363 flows.

364 For modeling purposes, available soil and segments are the main continuous variables,
 365 and available space and fullness ratio of the spoil pile and segment storage are the other pertinent
 366 continuous variables. For example, to calculate available soil, Equation 2 is used as follows:

$$\text{Available soil}(t_2) = \text{Available soil}(t_1) + \frac{d(\text{Soil inflow} - \text{Soil outflow})}{dt} \times dt$$

367 For the spoil pile fullness ratio, since the size of the spoil pile does not change, its fullness ratio
 368 can be calculated using Equation 5 and 11 as follows:

$$\text{Spoil pile fullness ratio}(t_2) = \text{Spoil pile fullness ratio}(t_1) + \frac{\frac{d(\text{Available soil})}{dt}}{\text{Spoil pile size}} \times dt$$

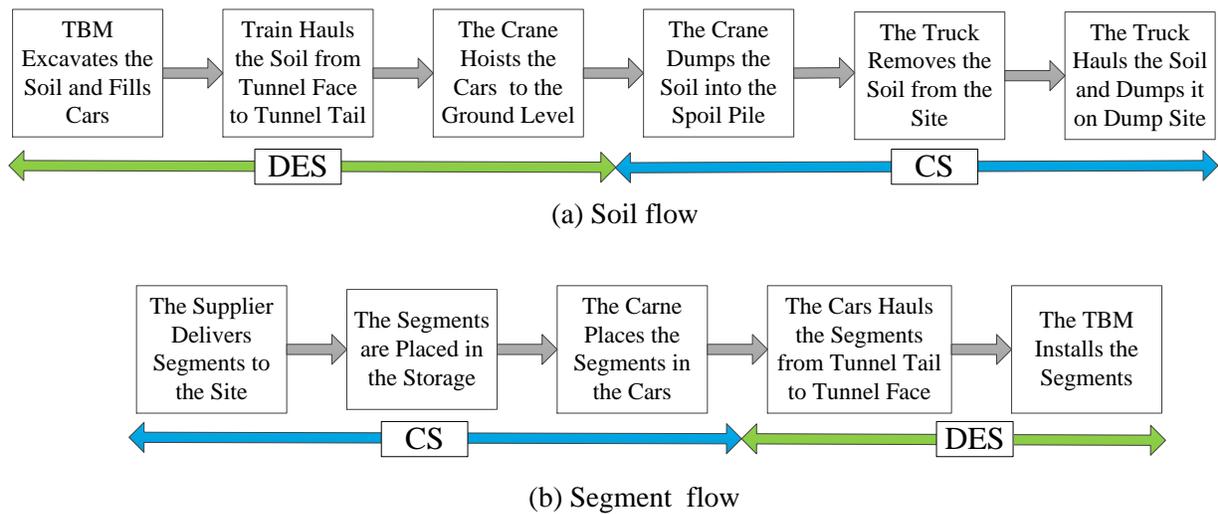
369 Replacing Equation 9 in the above Equation, spoil pile fullness ratio is calculated as:

$$\text{Spoil pile fullness ratio}(t_2) = \frac{\text{Available soil}(t_1)}{\text{Spoil pile size}} + \frac{\frac{d(\text{Available soil})}{dt}}{\text{Spoil pile size}} \times dt$$

370 Following the discussion presented in the “Research Methodology” section about DES
 371 and CS interactions, the DES part of the model adjusts the soil inflow rate when the crane dumps
 372 the soil from the cars to the spoil pile, which is done by a discrete change made to a continuous
 373 variable. The CS part of the model, on the other hand, adjusts the soil outflow rate, which can

374 also be changed through the interaction of DES and CS. Another interaction between the DES
 375 and CS parts of the model can be done once a continuous variable achieves a threshold value that
 376 may cause an event to occur or to be scheduled. This interaction is discussed where the
 377 managerial actions are introduced later.

378 In addition to the hybrid model, a pure DES model was built to compare the results of the
 379 two approaches in this case study.



380
 381
 382

Figure 4: Soil and segment flows

Table 1: Main characteristics of the project

Parameter	Value
Tunnel length	1030 (m)
TBM penetration rate	Beta (6,4,0.38,0.59)* (m/hr)
Survey duration	Beta (9,2,3,7) (hr)
Lining duration	Beta (1,1,0.2,0.3)
TBM reset duration	0.25 (hr)
Working shift hours	8 (hr)
Soil removal (outflow) rate	Uniform (26.5, 32.5)** (m ³ /shift)
Segment delivery (inflow) rate	Uniform (45, 50) (segment/ 2 days)

384

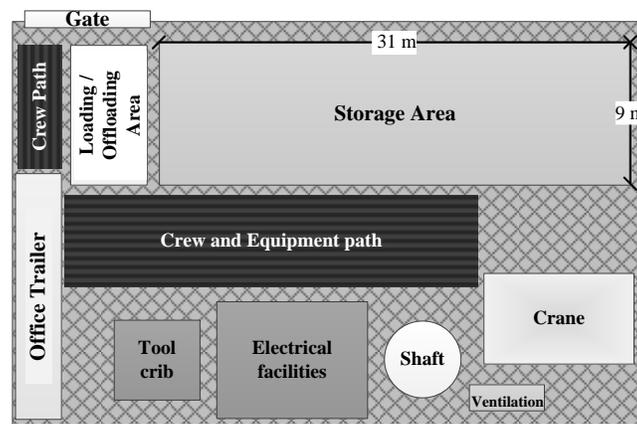
385 *Beta (a, b, c, d) is the beta probability distribution, where a and b are the shape parameters, and
 386 c and d are the lower and higher bounds, respectively.

387 **Uniform (x,y) is the uniform probability distribution, where x and y are the lower and higher
 388 bounds, respectively.

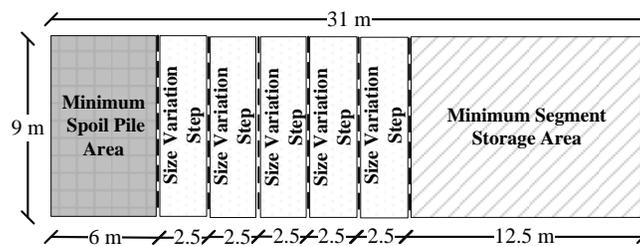
389 The schematic site layout of the project is depicted in Figure 5(a). As seen in this figure,
 390 it is a congested site, generally located in municipal areas, and the position of the shaft, crew
 391 trailer, tool crib, ventilation system, electrical facilities, loading/offloading area, crane, and
 392 crew/equipment path have been determined. There is also a storage area accommodating the
 393 spoil pile and segment storage. The primary objective of this case study is to identify how to split
 394 this area between these two facilities efficiently.

395 Initially, a unique unit of measure for the material quantity and facility size should be
 396 determined. For the soil, volume is measured in m³ and the size of the spoil pile is measured by

397 the maximum soil that can be stored in it. For segments, the number of segments is the unit of
 398 measure because the segments are identical. In this case study, each segment occupies $1.5 \text{ m} \times$
 399 2.5 m area including the required gap between the segments, while 4 segments, required for
 400 lining 1 m of the tunnel, are stacked on each other. Therefore, the size of the segment storage is
 401 estimated as the maximum number of segments that can be stacked in it. Moreover, managers
 402 have specified constraints for the minimum size of the spoil pile and segment storage as $9 \text{ m} \times 6$
 403 m and $12.5 \text{ m} \times 9 \text{ m}$, respectively, based on the rough estimation of the production rate. As a
 404 result of specifying minimum size of spoil pile and segment storage, the rest of the area can be
 405 split between them. However, based on the width of segments (2.5 m), it is reasonable to define
 406 size variation steps as 2.5 m ; other than that, the area is wasted for the segment storage. Figure 5
 407 (b) depicts the position and minimum size of the spoil pile and segment storage, and variation
 408 size steps.



(a) Site layout



(b) Material storage

409

410

Figure 5: Schematic view of the tunnel site layout

411 In addition to the site layout constraints, the interdependency of diverse planning
412 decisions and managerial actions should be taken into account. Figure 6 shows the complex
413 dependency between variables for the spoil pile and segment storage area (note that causal the
414 loop diagram was used only to illustrate the dependency between variables, and system dynamics
415 models have not been used in this paper). For instance, as shown in Figure 6, increasing the
416 production rate increases the need for space in the spoil pile, and simultaneously reduces the
417 need for space in the segment storage area. Increasing the production rate can induce lack of
418 space in the spoil pile which will halt production. In addition, two links between segment storage
419 size and spoil pile size show the dependency between them, which imply that increasing the
420 segment storage size reduces the spoil pile size, and vice versa. Figure 6 also specifies the
421 planning decisions from different disciplines integrated in a unified model, and the managerial
422 actions. In this project, four managerial actions are considered. First, when lacking space in the
423 spoil pile (when its fullness ratio reaches 90%), the soil outflow is doubled by deploying an extra
424 truck until the fullness ratio reaches 30%. Second, when lacking space in the segment storage
425 area (when its fullness ratio is more than 80%), the segment inflow is reduced to half by
426 procuring fewer segments delivered to the site until the fullness ratio reaches 50%. If there is no
427 space for incoming segments, they are stored off-site. The forth action is to prevent production
428 interruptions due to segment stock-out. When the fullness ratio of the segment storage area is as
429 little as 10%, the segment inflow is doubled by procuring more segments until the fullness ratio
430 reaches 50%. Taking these actions may take time which poses a delay between the times that
431 reaching the threshold is detected and the action is in effect. The symbol (||) on the arrows
432 represents this delay. For increasing and decreasing the soil outflow, the delays are 10 hours and
433 1 hour, respectively, and for increasing and decreasing the segment inflow, the delays are 10
434 hours and 1 hour, respectively. However, the action of using the off-site segment storage is taken

435 immediately. The managerial actions are modeled through the interaction of the DES and CS
 436 parts of the model. To this end, a specific element in the model continuously watches the value
 437 of the continuous variables to detect whether it reaches the specified threshold. If it does, the
 438 desirable changes in the related DES and/or CS parts are instantly made or scheduled to be made.

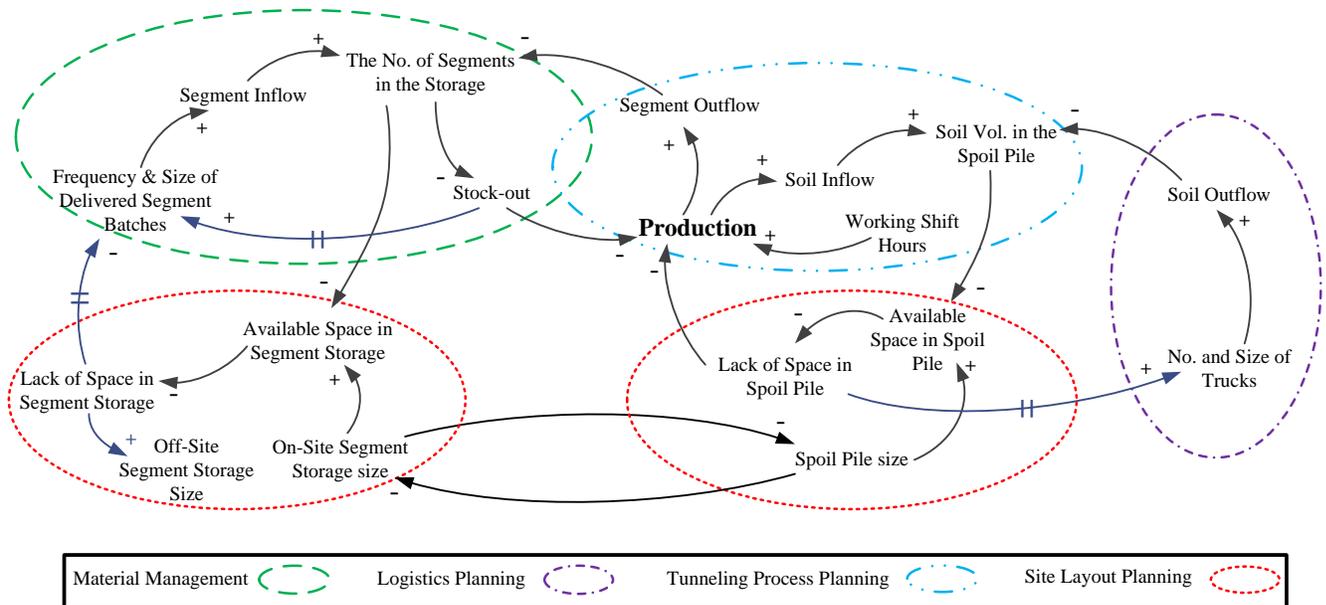


Figure 6: Dependency of the variables from different disciplines

441 This case study aims to quantitatively analyze the impact of the segment storage and spoil
 442 pile size on the project time and cost, and determine their optimum sizes. Thus, the summation of
 443 the following costs is defined as an evaluator function:

- 444 • Tunneling operation costs: crew and equipment costs for tunneling operation, equal to
 445 \$890 per hour.
- 446 • Permanent truck costs: operation costs of the truck working permanently in the project,
 447 equal to \$170 per hour.

448 • Extra truck costs: hourly cost of the extra truck operation, which is \$170 per hour, and
449 administration costs, which equal \$500 per the number of times that the extra truck is
450 deployed or released.

451 • Increasing or reducing segment delivery rate costs: administration costs, equal to \$1000
452 per the number of times that the segment inflow is increased or decreased.

453 • Off-site segment storage costs: fixed costs for double handling of the segments from the
454 off-site storage to the on-site storage, \$30 per segment, and time-dependant costs for
455 maintaining the batches in the off-site storage, \$5 per segment per day.

456 It should be noted that some other factors (e.g. material scheduling parameters) may exist
457 and have not been considered in the model as they were beyond the scope of this study. The built
458 model was examined for the scenarios presented in Table 2. In these scenarios, the size of the
459 spoil pile and segment storage, as well as the number of shifts per day (each shift is 8 hours),
460 vary. The following assumptions are made throughout when building the models:

- 461 • different shifts (day and night shifts) do not affect the productivity of the workers,
- 462 • the effect of changing the size of the spoil pile and the segment storage on the
463 loading/unloading time of the soil and segments is negligible, and
- 464 • at the beginning of the project, 48 segments are available in the storage, and no soil exists
465 in the spoil pile.

466

Table 2: Characteristics of the examined scenarios

Scenario #	No. of Shifts	Size #	Spoil Pile Dimensions	Spoil pile size (m ³)	Segment Storage Dimensions	Segment storage Size (No. of segments)
Scenario #1	1 shift	Size#1	9×6	124.2	9×25	240
Scenario #2		Size#2	9× 8.5	175.95	9×22.5	216
Scenario #3		Size#3	9× 11	227.7	9×20	192
Scenario #4		Size#4	9×13.5	279.45	9×17.5	168
Scenario #5		Size#5	9×16	331.2	9×15	144
Scenario #6		Size#6	9×18.5	382.95	9×12.5	120
Scenario #7	2 shifts	Size#1	9×6	124.2	9×25	240
Scenario #8		Size#2	9×8.5	175.95	9×22.5	216
Scenario #9		Size#3	9×11	227.7	9×20	192
Scenario #10		Size#4	9×13.5	279.45	9×17.5	168
Scenario #11		Size#5	9×16	331.2	9×15	144
Scenario #12		Size#6	9×18.5	382.95	9×12.5	120

468

469 The results of running the models 100 times are presented in Table 3 and Figure 7.

470 Comparing the total cost of the project reveals that Size #4 and Size #5 have the lowest costs for
471 the 1 shift and 2 shift plans, respectively. In the 1 shift plan, the project cost ranges from
472 \$3,541,839 to \$3,457,255, and in the 2 shift plan, it ranges from \$3,445,140 to \$3,391,922, by
473 changing the facility sizes. This range is about 2.4% and 1.6% of the total cost for the 1 shift and
474 2 shift plans, respectively. By changing the facility size, the project time ranges about 1.8% in

475 both shift plans. These ranges illustrate the significance of the facility size on the project cost and
476 time, and the importance of making the right decision on this matter. Comparing the cost
477 distribution of the scenarios with 1 shift and 2 shifts shows that the main difference between
478 them is the off-site segment storage cost, which is zero for the scenarios with the 2 shifts. The
479 significance of this cost may prompt the manager to reconsider the decision on the segment
480 procurement strategy (e.g. decreasing the frequency of the segment delivery) for the 1 shift plan,
481 which may increase the risk of the segment stock-out. In addition, the cost of deploying the extra
482 truck is considerable in all scenarios. The manager may want to revise the logistic plan (e.g.
483 increasing the size or the number of the permanent trucks), which may lead to increasing
484 permanent truck costs even more than the extra truck costs. Thus, to make these decisions and
485 compare the different options, a detailed cost analysis is necessary, which is complicated due to
486 the construction uncertainties and dynamic interactions between variables, as discussed earlier.
487 All these decisions can also affect the decision of facility sizes. It further substantiates the
488 significance of utilizing a simulation model as a planning tool, integrating the influencing
489 parameters from different disciplines at both strategic and operational levels, and quantitatively
490 analyzing the project cost.

491 Pure DES models were also experimented with for the described scenarios. Table 3
492 presents the variance between the cost and time of the hybrid and pure DES models. This
493 variance ranges from 2% to 14%, and 1% to 9% for the project cost and project time,
494 respectively. As discussed earlier, using the hybrid approach is more realistic as compared to the
495 pure DES approach. The same cases as the ones described in the “Research Methodology”
496 section can take place in the tunneling project, as follows:

- 497
- Case 1: when soil is dumped into the spoil pile and simultaneously the truck is being
- 498 loaded, or when the crane is hoisting the segments and simultaneously an incoming
- 499 segment batch is being offloaded to storage.
- 500
- Case 2: when segment stock-out happens.
- 501
- Case 3: when there is no space for offloading soil or segments.
- 502
- Case 4: when decisions are made to take managerial actions.
- 503

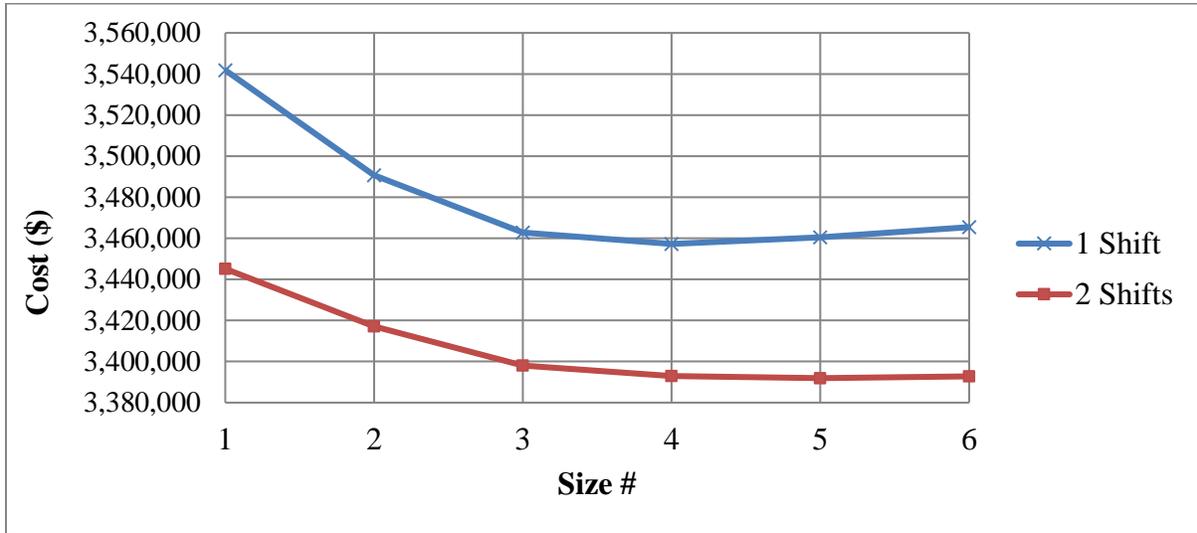
Table 3: Simulation results

Scenario #	Hybrid Model							DES Model		Total cost variance between hybrid and DES models	Total Time variance between hybrid and DES models
	Tunneling operation cost	Permanent truck cost	Extra truck cost	Cost of changing segment delivery rate	Off-site segment storage costs	Total cost (\$)	Total excavation time (hr)	Total cost (\$)	Total excavation time (hr)		
Scenario #1	2,681,387	515,023	243,621	3,000	98,808	3,541,839	3,013	4,027,269	3,215	14%	7%
Scenario #2	2,654,123	511,843	244,346	3,000	77,378	3,490,690	2,982	3,818,720	3,122	9%	5%
Scenario #3	2,639,049	511,197	241,250	3,000	68,364	3,462,860	2,965	3,704,772	3,059	7%	3%
Scenario #4	2,634,376	510,287	240,722	3,000	68,870	3,457,255	2,960	3,613,110	3,014	5%	2%
Scenario #5	2,633,671	510,790	239,475	3,000	73,548	3,460,485	2,959	3,589,313	3,000	4%	1%
Scenario #6	2,633,535	511,696	237,609	3,060	79,595	3,465,495	2,959	3,547,856	2,981	2%	1%
Scenario #7	2,680,863	514,915	243,982	5,380	0	3,445,140	3,012	3,803,115	3,294	10%	9%
Scenario #8	2,655,021	512,019	244,535	5,480	0	3,417,056	2,983	3,681,382	3,194	8%	7%
Scenario #9	2,639,410	511,152	241,515	6,060	0	3,398,137	2,966	3,581,095	3,100	5%	5%
Scenario #10	2,634,830	509,979	241,073	7,060	0	3,392,942	2,960	3,519,920	3,046	4%	3%
Scenario #11	2,633,017	510,845	239,260	8,800	0	3,391,922	2,958	3,491,348	3,020	3%	2%
Scenario #12	2,632,962	511,293	237,612	10,960	0	3,392,826	2,958	3,475,568	3,003	2%	1%

505

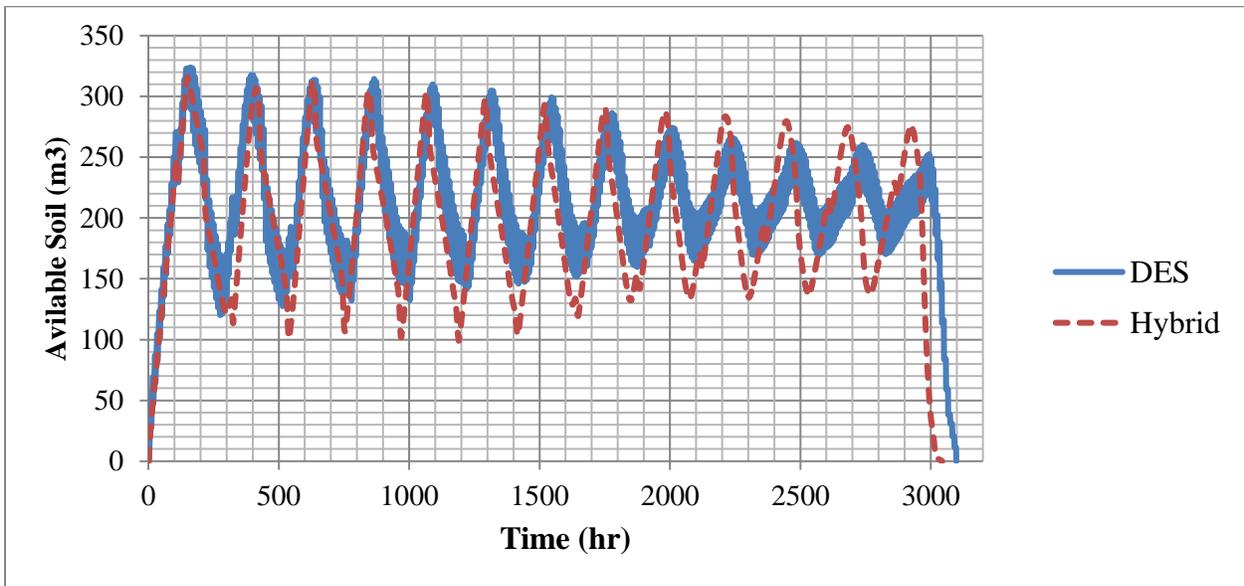
506 As an example to show the discrepancy between these approaches for modeling material
507 flow within facilities, Figure 8 displays the available soil in the spoil pile (the average values on
508 all the runs) in the optimum scenario (i.e. Scenario #11) for both DES and hybrid models.

509



510

511 Figure 7: Total costs of the project for different scenarios resulted from hybrid simulation models



512

513 Figure 8: Available soil in the spoil pile over the project time in Scenario #11 resulted from DES
514 and hybrid simulation models

515 **Summary and Conclusion**

516 Sizing material-dependant facilities is a complicated problem due to the interdependency
517 of the influencing factors, and dynamic interactions between them. In this research, the

518 production of construction operations was identified as a major factor affecting the size of this
519 kind of facility, and simulation was used to more accurately estimate production rate and
520 dynamically model the mutual impacts of facility size and the production rate. The main
521 contributions of this study are summarized as follows:

- 522 • building a simulation model that integrates construction process and material flow
523 modeling with facility size modeling,
- 524 • quantitatively analyzing the impact of facility size on the project time and cost,
- 525 • modeling managerial actions for resolving space shortage, and
- 526 • integrating variables and constraints of different disciplines, such as site layout planning,
527 material management, logistics and construction operation planning, influencing material
528 flow in a unified model.

529 To simulate projects at both strategic and operational levels, and enhance modeling
530 accuracy, hybrid discrete-continuous simulation was employed. Then, applicability and
531 sophistication of the methodology was studied in a tunneling project. Having compared the
532 results of the hybrid simulation models with the pure DES models in the case study, the
533 superiority of the proposed method was demonstrated. The proposed approach can also be
534 applied to other kinds of construction projects in which space for facilities is a critical problem,
535 and the impact of the facility size on the project cost needs to be assessed. Knowing the fact that
536 facility location is another attribute of the facilities that can affect the project cost, developing a
537 holistic model to incorporate decision making on the facility size and the location simultaneously
538 into construction site layout planning can be studied. In future research, the developed model can
539 also be integrated with other simulation models such as cell-based models and agent-based
540 models to enhance its capabilities from different aspects (e.g. modeling workspace and

541 equipment and worker movements on the site).

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