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

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Abstract

Sizing temporary facilities is a crucial task in construction site layout planning due to its significant impact on project productivity and cost. This paper describes a simulation-based approach for modeling the size of facilities that temporarily contain materials in construction projects. Different methods have been introduced for estimating the required size of this kind of facility; however, space limitations, particularly on congested sites, may not allow the planner to allocate the estimated space to the facilities. This study aims at quantitatively analysing the impact of facility size on the project and modeling the managerial corrective actions to remedy the space shortage in facilities. To this end, a hybrid discrete-continuous simulation technique is adopted. Simulation is superior in modeling dynamic interactions between variables as well as modeling construction processes with inherent uncertainties. The combination of discrete and continuous simulation is used to enhance accuracy and model the project at both operational level (i.e. activity level with higher level of detail) to estimate production rate, and strategic level (i.e. macro level with lower level of detail) to account for some construction planning decisions such as material management variables. The novelty of this study is analyzing the impact of facility size on the project time and cost, while managerial actions taken to resolve space shortages are modeled, and interdependent influencing parameters of the different disciplines, such as site layout, material management, logistics and construction process planning are integrated in a unified model. The applicability and suitability of the proposed approach is demonstrated in layout planning of a tunneling project site.

Key words: s*ite layout planning, simulation, hybrid discrete-continuous simulation, sizing temporary facilities, material management, construction planning.*

Introduction

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

Facilities occupy space on sites. Space is an important resource in construction projects (Hegazy and Elbeltagi, 1999), so this resource should be used efficiently through optimum facility size planning. On small sites, sizing facilities is more critical because of limitations on the space and the consequences of inaccurate estimation of facility size. In general, improperly sizing facilities imposes congestion and space conflicts, which adversely influences the productivity and safety of projects (Halligan et al., 1994; Akinci et al., 1998; Winch and North, 2006). Specifically, underestimation of the size of material-dependant facilities causes space shortage for that facility, which can result in loss of productivity, and incur extra cost for resolving the encountered problems. For example, insufficient size allocation of a material storage can cause lower productivity in many ways, such as: interrupting material flow when there is no space for offloading materials, and spending more time on finding and handling materials when the storage is congested. On small sites, however, insufficient space for material-dependant facilities may be unavoidable, and in these cases, the planner should alter some construction planning decisions (e.g. material delivery plan) to reduce the need for space on the site. As such, considering those variables as well as the corrective actions to resolve space shortages is vital in modeling facility size. On the other hand, overestimation of facility size can impose spatial conflicts and lack of space for the other facilities. On large sites where space is not limited, facility installation and maintenance costs are the drivers of facility size. As an objective of this research, the impacts of material-dependant facility size on different aspects of a project such as productivity, material flow, size of other facilities and project cost and time are quantitatively evaluated.

Although sizing facilities is considered a part of site layout planning tasks (Tommelein, 1992), most studies in construction site layout planning focused on optimizing the position of the facilities (e.g. Ning, et al. (2010), Ning, et al. (2011), and Xu & Li (2012)), and less attention was paid to efficiently planning the size of the facilities. In the context of site layout planning, Elbeltagi and Hegazy (2001) proposed a knowledge-based method to identify required areas of a number of temporary facilities using IF-THEN rules. The implemented rules were defined on the basis of personnel requirements, estimated quantity of work, production rate of resources, availability of site space, and cost, but did not account for possible variation of these parameters throughout the project. In space scheduling, Zouein and Tommelein (2001) categorized the profile of the space needs for facilities into resource independent, which was fixed, and resource dependant which was either fixed or variable over the project. For the variable profiles, space needs might decrease linearly or fluctuate between minimum and maximum levels as the corresponding activities progress, which are over-simplified assumptions. The size of the facilities is also addressed in the unequal-area facility layout problems (e.g. studies by Zhang & Wang, (2008) and Li & Love (2000)), in which facilities are assigned to predetermined locations, and due to the size constraints, large facilities cannot be assigned to small size locations. Although the size of the facilities is considered in this assignment, this approach cannot quantitatively assess the impact of the facility size on the project time or cost.

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

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

For modeling dynamics and uncertainties inherent in construction projects, simulation has often been utilized in the literature (e.g. Tang et al. (2013) and Said et al. (2009)). In relevant research, Ebrahimy et al. (2011) used simulation to model supply chain management in tunneling construction, and evaluated the effect of space shortage for storing concrete segment liners, located on supplier’s sites and the construction site, on the project time. This research demonstrated the capability of simulation to model storage capacity and the effect of space shortage on the project time. Alanjari et al. (2014) integrated simulation with genetic algorithm to optimize material placement layout in yard laydowns. RazaviAlavi et al. (2014) also used a simulation-based approach to more accurately model variation of the space required for facilities throughout construction projects. However, these studies overlooked the site layout constraints in sizing facilities, and could not model the situation in which the required space for facilities is not available on the site. Cellular automata (CA) is another technique that can be used for modeling space represented by uniform grids. Zhang et al. (2007) used CA to model space resources in construction simulation, analyze spatial conflicts, and visualize the occupied space on construction sites. Agent-based simulation can also be used to model some features in layout planning such as workers' movements. Said et al. (2012) used agent-based simulation to evaluate performance of labor emergency evacuation plans considering geometry of the site.

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

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

Research Methodology

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

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

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

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

For modeling material flow, different perspectives exist. Materials are naturally either continuous (e.g. soil, cement, concrete and oil) or discrete (e.g. precast concrete panels, steel pieces and bricks). However, the flow of continuous materials can be modeled discretely if the materials' containers, such as a bucket of soil and a tanker of oil, are considered. The flow of discrete materials can also be modeled continuously if the materials are aggregated. Considering this fact, either discrete event simulation, continuous simulation or combined discrete-continuous simulation can be utilized to model material flow.

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

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

$$\mathrm{S}(\mathrm{t}_2) = \mathrm{S}(\mathrm{t}_1) + \frac{\mathrm{ds}}{\mathrm{dt}}\,\mathrm{dt} \tag{1}$$

where $S(\mathrm{t}_2)$ and $S(\mathrm{t}_1)$ are the value of the continuous variable S at time t_2 and t_1, respectively ($\mathrm{t}_2 = \mathrm{t}_1 + dt$), and ds/dt is change rate of the continuous variable. CS is more suitable to model at the strategic level with aggregated data (e.g. macroscopic models of supply chain (Pierreval, et al., 2007)), where lower level of details and less modeling efforts than DES are needed (Reggelin & Tolujew, 2011). CS is mostly used to predict the long-term behavior of the project and model managerial corrective actions.

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

When adopting CS for modeling material flow, the available material within a facility can be calculated using Equation (2), which implies that available material within the facility at time t_2 equals the available material at time t_1 plus the differences of material inflow and outflow, where $\mathrm{t}_2 = \mathrm{t}_1 + dt$.

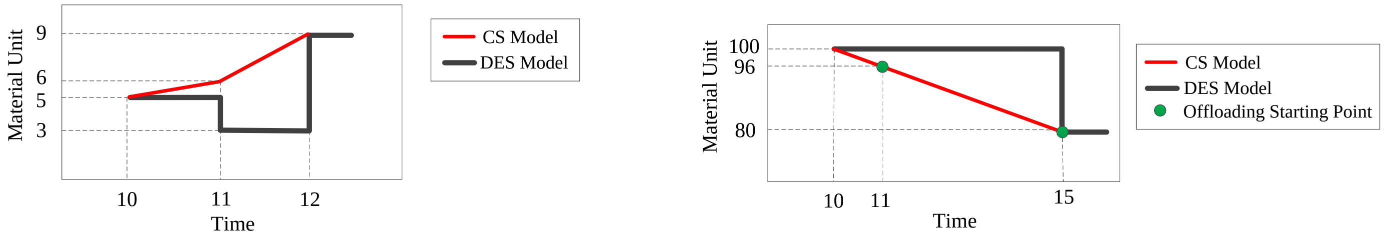
$$\begin{aligned}&\text{Available material}(\mathrm{t}_2)\\&= \text{Available material}(\mathrm{t}_1) + \frac{\mathrm{d}(\text{Material inflow} - \text{ Material outflow})}{\mathrm{dt}} \times \mathrm{dt}\end{aligned} \quad (2)$$

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

- Case 1 (when material inflow and outflow happen simultaneously): assume that at time 10, 5 units of material are available in the facility. At this time, 6 units of the material come into a facility with the rate of 3 units of material per unit of time. At the same time, 2 units of material are going out of the facility with the rate of 2 units of material per unit of time. Comparing the result of discrete and continuous models for the quantity of available material over time depicted in Figure 1 (a), it is seen that the continuous model is more accurate, although the final result is the same.
- Case 2 (when there are not enough material units to start an activity): assume that there is only one unit of material in stock at time 10 and an activity which needs 2 units of material to start is waiting for delivery of the material. At this time, a batch of material including 6 units with the rate of 1 unit of material per unit of time is coming to the

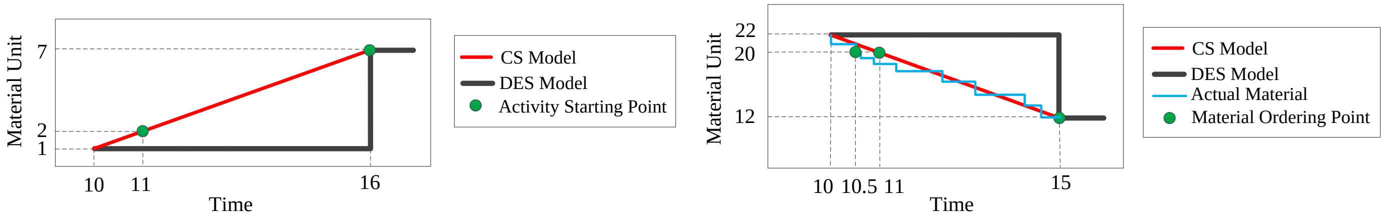
stock. In the DES model, the activity cannot start until all the units have been offloaded, at time 16; however, in the CS model, the activity starts as soon as 2 units are available, at time 11, as shown in Figure 1 (b).

- Case 3 (when there is not sufficient space for incoming material): assume that the capacity of a facility is 100 units of material and it is full. An incoming batch including 4 units of the material is waiting for a space to be offloaded at time 10. At the same time, 20 units of the material are going out of the facility with the rate of 4 units of material per unit of time. As shown in Figure 1 (c), in the DES model, the incoming batch cannot be offloaded until the whole 20 units leave the facility at time 15, while in the CS model it is possible to offload it at time 11, which is more accurate.
- Case 4 (taking managerial actions when material level is reaching a threshold): DES is a less reliable tool to model managerial actions because of its inconsistent time step size (Lee et al., 2007). Assume that the strategy of a manager is to order material when the available material units in the stock are less than 20 units. At time 10, the available material is at 22, and at the same time, 10 units of material are going out of the stock with the rate of 2 units of material per unit of time. In the CS model, the material order is placed at time 11, while in the DES model, it is placed at time 15, which can increase the risk of occurring stock-out, as depicted in Figure 1 (d).



(a) Case 1

(c) Case 3



(b) Case 2

(d) Case 4

Figure 1: CS versus DES for four example cases

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

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

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

Modeling Facility Size Underlying Material Flow

Decisions on the size of material-dependant facilities can be made directly on the basis of the estimated quantity of the available material placed inside the facility. To this end, the quantity of material, the occupied space/area, and the facility size (capacity) should be measured by a unique unit, which depends on the type of the material and what is convenient for the modellers. After measuring available material and facility size by a unique unit, the next step is to calculate other relevant parameters (e.g. available space and fullness ratio of the facility) to these variables, required for different modeling purposes like modeling managerial actions. These parameters are considered continuous variables in the model because they are related to another continuous variable: available material within a facility. That is, the changes of these variables also occur continuously. If the facility size changes over time, it should also be defined as a continuous variable. Utilizing Equation 1, facility size is computed, as in Equation 3:

$$\mathrm{Facility\ size}(\mathrm{t}_2) = \mathrm{Facility\ size}(\mathrm{t}_1) + \frac{\mathrm{d}(\mathrm{Facility\ size})}{\mathrm{dt}} \times \mathrm{dt} \tag{3}$$

where facility size(t_2) and facility size(t_1) are the values of facility size at times t_2 and t_1, respectively, and d(Facility size)/dt is the rate of changing facility size (t_2=t_1+dt). Then, utilizing

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

$$\text{Available space}(\mathrm{t}_2) = \text{Available space}(\mathrm{t}_1) + \frac{\mathrm{d}(\text{Available space})}{\mathrm{dt}} \times \mathrm{dt} \tag{4}$$

$$\text{Fullness ratio}(\mathrm{t}_2) = \text{Fullness ratio}(\mathrm{t}_1) + \frac{\mathrm{d}(\text{Fullness ratio})}{\mathrm{dt}} \times \mathrm{dt} \tag{5}$$

According to definitions of available space (Equation 6) and fullness ratio (Equation9), as well as Equations 2 and 3, the change rate of available space and fullness ratio can be calculated. The calculations for the available space are as follows:

$$\text{Available space} = \text{Facility size} - \text{Available material} \tag{6}$$

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

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

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

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

$$\text{Fullness ratio} = \frac{\text{Available material}}{\text{Facility size}} \tag{9}$$

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

$$\frac{d(\text{Fullness ratio})}{dt} = \frac{\frac{\mathrm{d}(\text{Available material})}{\mathrm{dt}}}{\text{Facility size}(\mathrm{t}_1)} - \frac{\text{Available material }(\mathrm{t}_1)}{\text{Facility size}^2(\mathrm{t}_1)} \times \frac{\mathrm{d}(\text{Facility size})}{\mathrm{dt}} \tag{11}$$

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

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

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

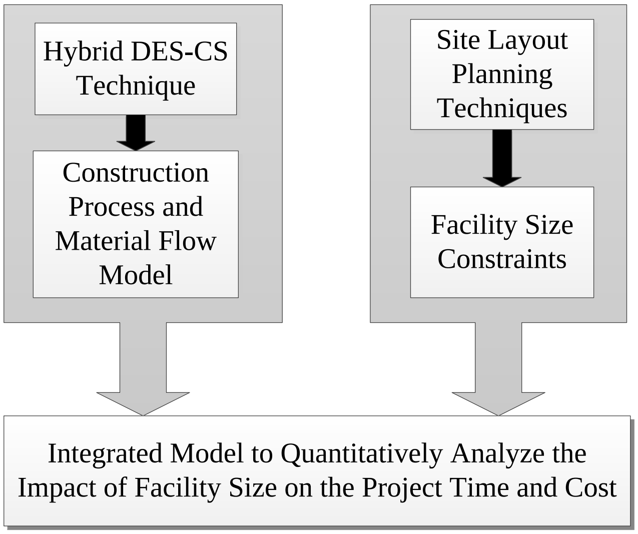


Figure 2: Adopted techniques to build the integrated model

Modeling Managerial corrective Actions

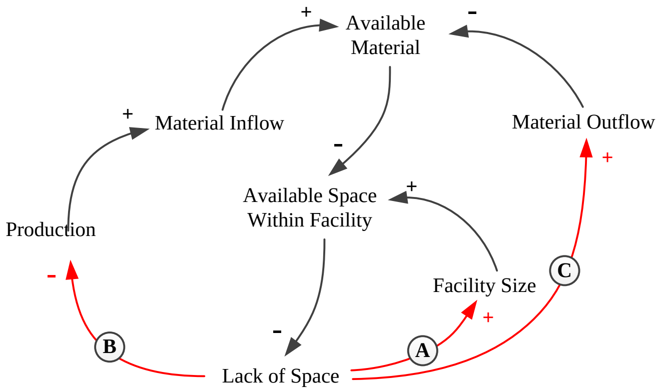
Managerial corrective actions are mostly disregarded when modeling real-world projects by traditional construction simulation methods (Lee et al., 2009). As discussed earlier, the combined discrete-continuous simulation method facilitates enhancing accuracy in modeling managerial actions. This study mainly concentrates on the managerial actions for resolving space shortage problems; however, there is no barrier to model the actions for other matters. Changing facility size is one of the managerial actions taken when lacking space. Altering planning decisions and changing material inflow and outflow are other managerial actions that can influence the available material, and subsequently, reduce the demand for space within a facility. These planning decisions may be pertinent to construction process planning (e.g. altering working shift hours to change the system production rate), material management (e.g. altering material procurement plan to change delivered material rate to the site), or logistics (e.g. altering the number of material handlers to change material flow rate on the site).

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

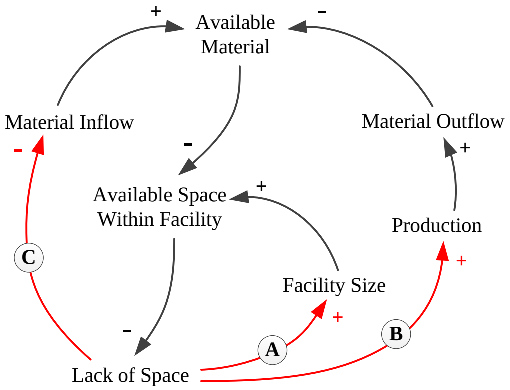
- Action A: increasing facility size.
- Action B: reducing system production rate (e.g. reducing working shift hours, reducing employed resources, or even halting the production).
- Action C: increasing material outflow rate (e.g. employing more resources removing materials from the facility).

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

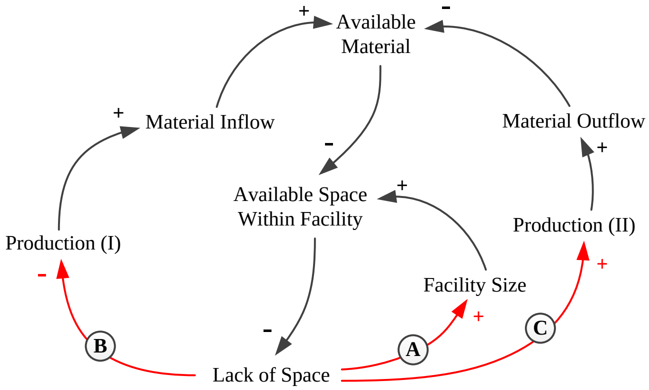
In the next section, a case study demonstrates the capabilities of simulation in modeling these complex processes.



(a) Group I



(b) Group II



(c) Group III

Figure 3: Managerial actions for three groups

Case Study

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

The segment flow is different, as depicted in Figure 4 (b). The segments are delivered from a supplier to the site, and offloaded in the segment storage area. Then, when needed, the segments are taken from storage using the crane to place them into cars. The cars transport the segments from the tunnel tail to the tunnel face. Finally, they are installed by the TBM. According to the described material flows, the spoil pile and the segment storage are categorized as Group (I) and Group (II) of the material-dependent facilities, respectively. In addition to activities involved in material flow, the other activities corresponding to tunneling should be considered to model the construction process. These activities include resetting the TBM, surveying, and rail track extensions (see Ruwanpura et al. (2001) for further information on the tunneling process). Due to uncertainties in the tunneling construction process, particularly the geotechnical parameters of the soil, as well as the segment supply and productivity of the soil removal, some input data such as the TBM penetration rate, the segment inflow and soil outflow rates, and the duration of most activities are considered stochastically in the simulation model. Table 1 gives information on the main characteristics of the case study. In the simulation model built in the Simphony environment (Hajjar and AbouRizk, 1996), Simphony.NET 4.0 version, the tunneling tasks at the operational level are modeled by DES as resource interactions are important for estimating tunneling production rate. The segment supply and the soil removal are modeled by CS at the strategic level, since a high level of detail (e.g. the precise information on the segment delivery time, truck availability time on the site for loading the soil, and the truck cycle time for dumping the soil on the dump site) is not available at the preplanning phase. Figure 4 also shows the utilized approaches in modeling different parts of the soil and segment flows.

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

$$\text{Available soil}(\mathrm{t}_2) = \text{Available soil}(\mathrm{t}_1) + \frac{\mathrm{d}(\text{Soil inflow} - \text{ Soil outflow})}{\mathrm{dt}} \times \mathrm{dt}$$

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

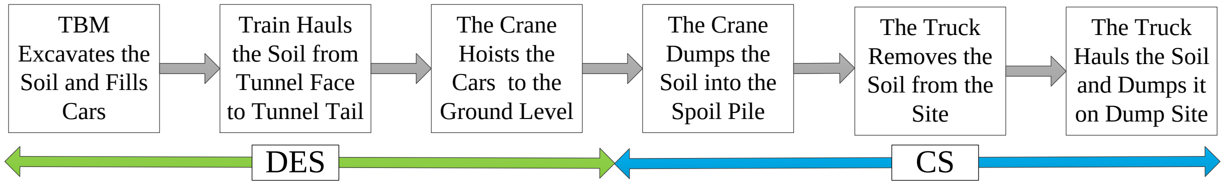
$$\text{Spoil pile fullness ratio}(\mathrm{t}_2) = \text{Spoil pile fullness ratio}(\mathrm{t}_1) + \frac{\frac{\mathrm{d}(\text{Available soil})}{\mathrm{dt}}}{\text{Spoil pile size}} \times \mathrm{dt}$$

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

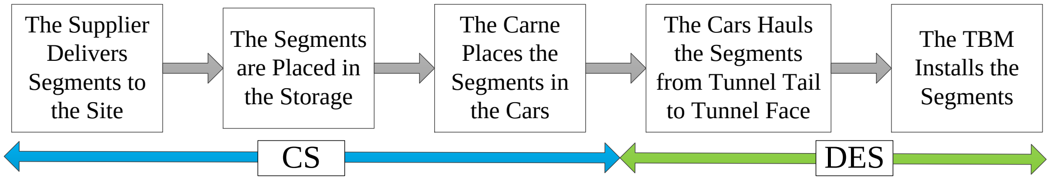
$$\text{Spoil pile fullness ratio}(\mathrm{t}_2) = \frac{\text{Available soil }(\mathrm{t}_1)}{\text{Spoil pile size}} + \frac{\frac{\mathrm{d}(\text{Available soil})}{\mathrm{dt}}}{\text{Spoil pile size}} \times \mathrm{dt}$$

Following the discussion presented in the “Research Methodology” section about DES and CS interactions, the DES part of the model adjusts the soil inflow rate when the crane dumps the soil from the cars to the spoil pile, which is done by a discrete change made to a continuous variable. The CS part of the model, on the other hand, adjusts the soil outflow rate, which can also be changed through the interaction of DES and CS. Another interaction between the DES and CS parts of the model can be done once a continuous variable achieves a threshold value that may cause an event to occur or to be scheduled. This interaction is discussed where the managerial actions are introduced later.

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



(a) Soil flow



(b) Segment flow

Figure 4: Soil and segment flows

Table 1: Main characterics of the project

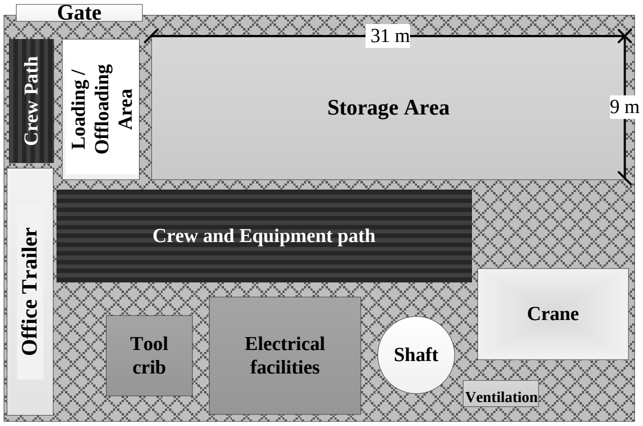
Parameter	**Value**
Tunnel length	1030 (m)
TBM penetration rate	Beta (6,4,0.38,0.59)* (m/hr)
Survey duration	Beta (9,2,3,7) (hr)
Lining duration	Beta (1,1,0.2,0.3)
TBM reset duration	0.25 (hr)
Working shift hours	8 (hr)
Soil removal (outflow) rate	Uniform (26.5, 32.5)** (m^3/shift)
Segment delivery (inflow)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

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

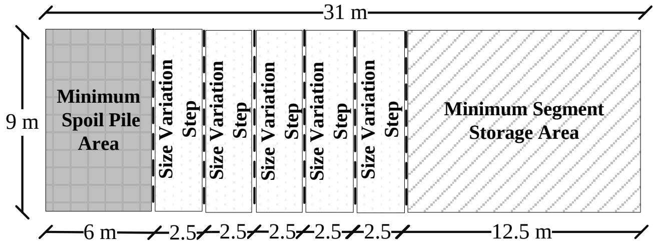
**Uniform (*x*,*y*) is the uniform probability distribution, where *x* and *y* are the lower and higher bounds, respectively.

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

Initially, a unique unit of measure for the material quantity and facility size should be determined. For the soil, volume is measured in m^3 and the size of the spoil pile is measured by the maximum soil that can be stored in it. For segments, the number of segments is the unit of measure because the segments are identical. In this case study, each segment occupies 1.5 m × 2.5 m area including the required gap between the segments, while 4 segments, required for lining 1 m of the tunnel, are stacked on each other. Therefore, the size of the segment storage is estimated as the maximum number of segments that can be stacked in it. Moreover, managers have specified constraints for the minimum size of the spoil pile and segment storage as 9 m × 6 m and 12.5 m × 9 m, respectively, based on the rough estimation of the production rate. As a result of specifying minimum size of spoil pile and segment storage, the rest of the area can be split between them. However, based on the width of segments (2.5 m), it is reasonable to define size variation steps as 2.5 m; other than that, the area is wasted for the segment storage. Figure 5 (b) depicts the position and minimum size of the spoil pile and segment storage, and variation size steps.



(a) Site layout



(b) Material storage

Figure 5: Schematic view of the tunnel site layout

In addition to the site layout constraints, the interdependency of diverse planning decisions and managerial actions should be taken into account. Figure 6 shows the complex dependency between variables for the spoil pile and segment storage area (note that causal the loop diagram was used only to illustrate the dependency between variables, and system dynamics models have not been used in this paper). For instance, as shown in Figure 6, increasing the production rate increases the need for space in the spoil pile, and simultaneously reduces the need for space in the segment storage area. Increasing the production rate can induce lack of space in the spoil pile which will halt production. In addition, two links between segment storage size and spoil pile size show the dependency between them, which imply that increasing the segment storage size reduces the spoil pile size, and vice versa. Figure 6 also specifies the planning decisions from different disciplines integrated in a unified model, and the managerial actions. In this project, four managerial actions are considered. First, when lacking space in the spoil pile (when its fullness ratio reaches 90%), the soil outflow is doubled by deploying an extra truck until the fullness ratio reaches 30%. Second, when lacking space in the segment storage area (when its fullness ratio is more than 80%), the segment inflow is reduced to half by procuring fewer segments delivered to the site until the fullness ratio reaches 50%. If there is no space for incoming segments, they are stored off-site. The forth action is to prevent production interruptions due to segment stock-out. When the fullness ratio of the segment storage area is as little as 10%, the segment inflow is doubled by procuring more segments until the fullness ratio reaches 50%. Taking these actions may take time which poses a delay between the times that reaching the threshold is detected and the action is in effect. The symbol (||) on the arrows represents this delay. For increasing and decreasing the soil outflow, the delays are 10 hours and 1 hour, respectively, and for increasing and decreasing the segment inflow, the delays are 10 hours and 1 hour, respectively. However, the action of using the off-site segment storage is taken immediately. The managerial actions are modeled through the interaction of the DES and CS parts of the model. To this end, a specific element in the model continuously watches the value of the continuous variables to detect whether it reaches the specified threshold. If it does, the desirable changes in the related DES and/or CS parts are instantly made or scheduled to be made.

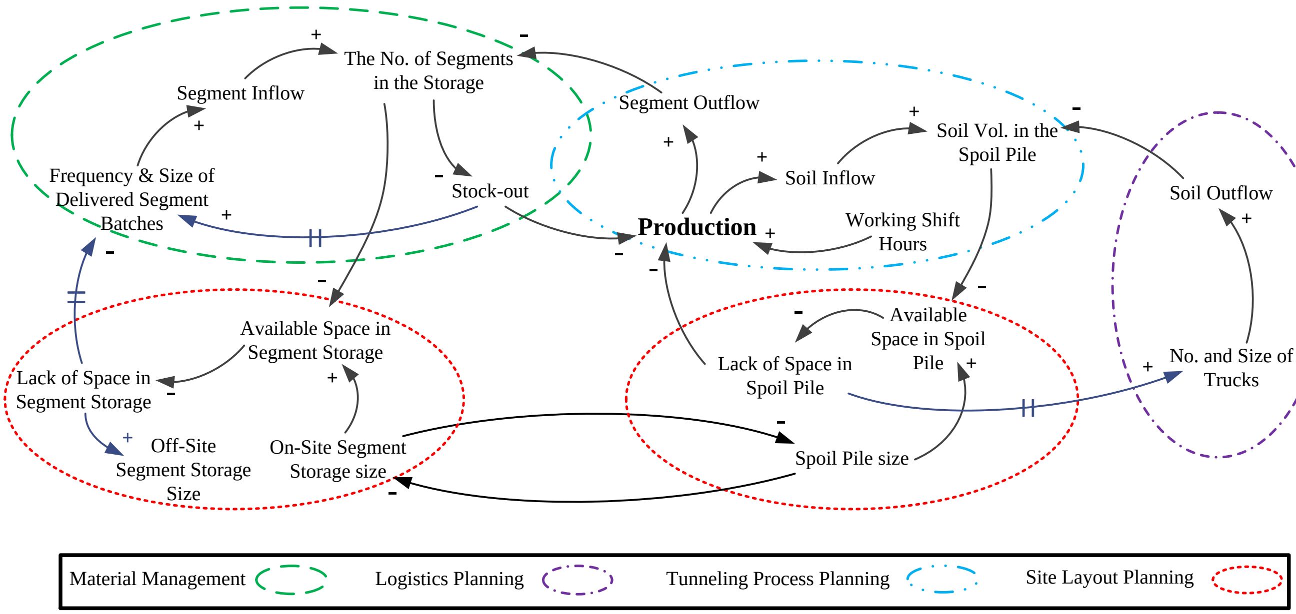


Figure 6: Dependency of the variables from different disciplines

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

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

- Extra truck costs: hourly cost of the extra truck operation, which is $170 per hour, and administration costs, which equal $500 per the number of times that the extra truck is deployed or released.
- Increasing or reducing segment delivery rate costs: administration costs, equal to $1000 per the number of times that the segment inflow is increased or decreased.
- Off-site segment storage costs: fixed costs for double handling of the segments from the off-site storage to the on-site storage, $30 per segment, and time-dependant costs for maintaining the batches in the off-site storage, $5 per segment per day.

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

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

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

The results of running the models 100 times are presented in Table 3 and Figure 7. Comparing the total cost of the project reveals that Size #4 and Size #5 have the lowest costs for the 1 shift and 2 shift plans, respectively. In the 1 shift plan, the project cost ranges from \$3,541,839 to \$3,457,255, and in the 2 shift plan, it ranges from \$3,445,140 to \$3,391,922, by changing the facility sizes. This range is about 2.4% and 1.6% of the total cost for the 1 shift and 2 shift plans, respectively. By changing the facility size, the project time ranges about 1.8% in both shift plans. These ranges illustrate the significance of the facility size on the project cost and time, and the importance of making the right decision on this matter. Comparing the cost distribution of the scenarios with 1 shift and 2 shifts shows that the main difference between them is the off-site segment storage cost, which is zero for the scenarios with the 2 shifts. The significance of this cost may prompt the manager to reconsider the decision on the segment procurement strategy (e.g. decreasing the frequency of the segment delivery) for the 1 shift plan, which may increase the risk of the segment stock-out. In addition, the cost of deploying the extra truck is considerable in all scenarios. The manager may want to revise the logistic plan (e.g. increasing the size or the number of the permanent trucks), which may lead to increasing permanent truck costs even more than the extra truck costs. Thus, to make these decisions and compare the different options, a detailed cost analysis is necessary, which is complicated due to the construction uncertainties and dynamic interactions between variables, as discussed earlier. All these decisions can also affect the decision of facility sizes. It further substantiates the significance of utilizing a simulation model as a planning tool, integrating the influencing parameters from different disciplines at both strategic and operational levels, and quantitatively analyzing the project cost.

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

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

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%

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

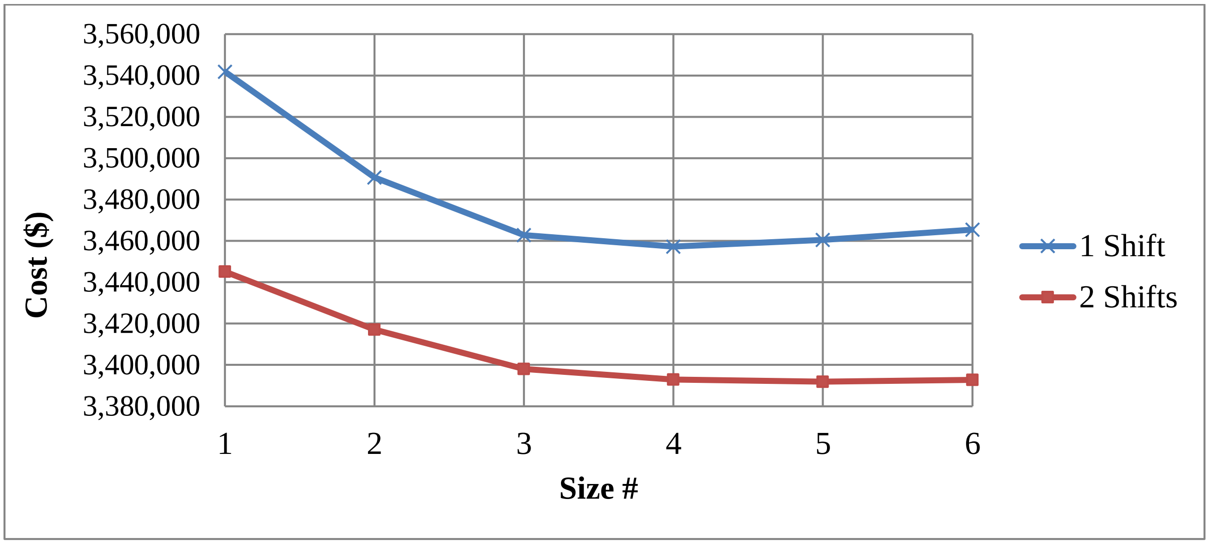


Figure 7: Total costs of the project for different scenarios resulted from hybrid simulation models

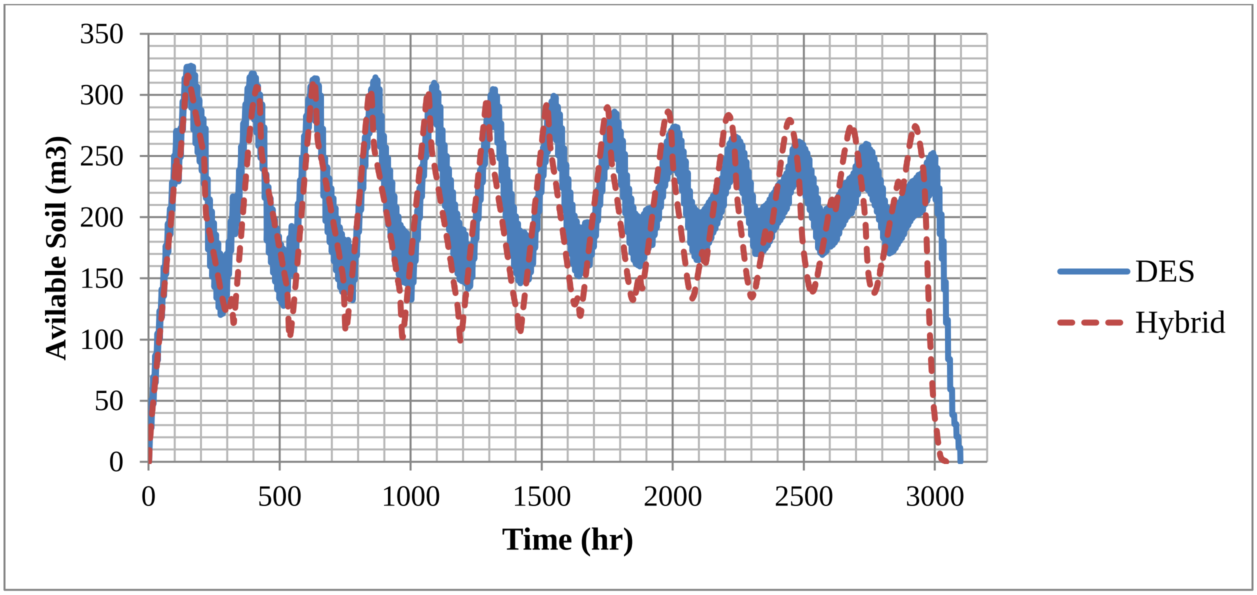


Figure 8: Available soil in the spoil pile over the project time in Scenario #11 resulted from DES and hybrid simulation models

Summary and Conclusion

Sizing material-dependant facilities is a complicated problem due to the interdependency of the influencing factors, and dynamic interactions between them. In this research, the production of construction operations was identified as a major factor affecting the size of this kind of facility, and simulation was used to more accurately estimate production rate and dynamically model the mutual impacts of facility size and the production rate. The main contributions of this study are summarized as follows:

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

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

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