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A Simulation-based Decision Support Tool for Integrating Site Layout and Construction Planning of Tunnelling Projects

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Purpose

Integrating construction and site layout planning in mechanised tunnel infrastructure projects is essential due to the mutual impacts of construction planning and site layout decisions. Simulation can incorporate site layout planning and construction planning of tunneling projects in a unified environment. However, simulation adoption by industry practitioners has remained relatively limited due the special skills required for building and using simulation models. Therefore, this research aims to create a simple-to-use simulation tool that supports site layout and construction operation planning of tunneling projects. This tool intends to promote the simulation application in the site layout planning.

Design/methodology/approach

The current paper proposes simulation as a decision support tool (DST) to provide an integrated environment for modeling tunnel construction operations, site layout and capturing the mutual impacts. A special purpose simulation (SPS) tool was customized and developed for typical mechanized tunnelling projects, by tunnel boring machines (TBM), to facilitate building the model and allow access to users with limited simulation knowledge.

Findings

The results show that the developed SPS tool is of great assistance to construction industry practitioners to analyze a variety of site layout and construction plan scenarios and make informed decisions based on its comprehensive and intuitive outputs.

Originality

The main contribution of this research is to promote simulation application in site layout planning of tunneling projects through the development of a simple-to-use tool, which has sufficient details for site

layout planning and constraints. The developed DST enables planners to make decisions simultaneously on the site layout, other construction planning variables and identify the most efficient plan.

Keywords: simulation, special purpose simulation, tunnel construction, site layout planning, decision support tool, construction planning.

1. Introduction

Site layout planning identifies the required types of temporary facilities and determines their size and location. The location of the facilities can directly affect the efficiency of on-site logistics and transportation (i.e., equipment, material, and worker transportation). Consequently, it can influence the productivity, time, and cost of construction projects. Moreover, space, which is an important resource in construction operations, can be used more efficiently by optimizing facility size. Space limitation is a significant concern for tunneling sites located in urban areas that should be addressed through optimal site layout planning.

In “mechanized tunneling” (referred to as ‘tunneling’ in this paper), on-site material transportation mainly comprises of transporting soil materials produced in the underground excavation from the shaft to the spoil pile—while also transporting the segments from the segment storage to the shaft to be installed in the tunnel. As a result, the location of the facilities maintaining the soil and segments (i.e., spoil pile and concrete segment storage) can affect the efficiency of on-site material transportation, and consequently, the overall tunneling production rate. Properly sizing such facilities is another critical decision in layout planning. On one hand, the tunneling production rate, the planning decisions on segment procurement, and the logistics of removing the soil from the site drive the quantity of soil and segments stored on the site. On the other hand, the space limitations on the site can constrain the space that can be allocated to the spoil pile and segment storage, which may lead to revising planning decisions, e.g., by increasing the number of trucks removing soil from the site, or by delaying segment delivery to reduce the space needs. However, making such decisions is a complicated due to dependency on the influencing factors and mutual impacts between the site layout and tunnel construction decision variables. For instance, delaying the segment delivery to address the storage space limitation could potentially increase the risk of segment stock-out and disrupt tunneling operations. Therefore, a DST is required to integrate site layout and construction planning in a unified model to account for all the influencing factor and capture their interrelationships. In addition, the inherent uncertainties in tunneling (e.g., variability of the excavation rate, delays in the segment supply, and TBM breakdown) need to be considered in the model. Simulation can be utilized as a suitable DST to address these needs due to its ability in modeling complex and dynamic relationships between variables, while also modeling uncertainties through Monte Carlo simulation and stochastic analysis. Despite the benefits mentioned above, simulation adoption by industry practitioners have remained relatively limited. Abdelmegid et al. (2020) identified "special skills required to develop simulation models" and "lack of proper simulation knowledge among construction practitioners" as significant barriers to adopting simulation modelling in the construction industry. To bridge these gaps, they recommend researchers to develop pre-defined construction-specific objects for reducing the skills, efforts, and time required to build simulation models. Therefore, this research aims to create a simple-to-use simulation tool that supports site layout and construction operation planning of tunneling projects. This tool intends to promote the simulation application in the site layout planning and facilitate building models for users with limited simulation knowledge.

In this paper, first, a literature review is presented. Next, the research methodology for the development of the DST is outlined. The steps for developing the DST and its implementation in a case study, followed by verification and validation, are stated in the following sections. In the last section, the summary and conclusion are presented.

2. Literature Review

Several studies have been conducted on improving construction site layout planning. Primarily, the studies have focused on locating facilities and identifying their optimal positions on the site. Reducing on-site transportation costs, and addressing health, safety, and environmental concerns are the main objectives of existing site layout optimization methods. Studies, such as Zhang and Wang (2008) and Kaveh and Vazirinia (2019), attempted to optimize the location of facilities by minimizing the sum of weighted distance function ($\sum w \times d$), which reduces the on-site transportation cost between facilities. In the given function, w represents the cost per meter of the distance between each two facilities, while d represents the distance between the facilities. Some studies, e.g., Elbeltagi et al. (2004) Cheng and Connor (1996), used the same function but subjectively identified 'w' as the rate of closeness between the facilities. However, the sum of weighted distance function (SWDF) does not realistically model the material, worker and equipment flow, and the interaction between facilities. This is because the estimate for *w* cannot reflect the reality of complex construction projects. For considering health, safety and environmental factors in site layout planning, different approaches have been developed. A plausible approach would be to consider them in relation to the subjective weights assigned to the interaction between facilities in the SWDF method. Another approach used by many researchers, such as Sanad et al. (2008) and El-Rayes and Said (2009), is to define health, safety, and environmental constraints as hard constraints, implying that they must be satisfied. Exclusion/inclusion constraints to limit the position of facilities outside/inside a zone and minimum/maximum distance between facilities are the typical constraints within this particular approach. Some researchers attempted to quantitatively evaluate the impacts of the site layout on health, safety, and environment. El-Rayes and Khalafallah (2005) and Ning et al. (2018) developed quantitative methods for evaluating different hazards, such as crane operation hazards, storing hazardous material, travel route intersections, noise, dust, and vibration on construction sites.

Optimizing the location of facilities has been of interest in the research, and different optimization methods have been experimented with to identify optimum or near optimum site layout. Due to the wide range of possible solutions, the heuristic and metaheuristic optimization methods, such as genetic algorithm (by Sanad et al. (2008); Said and El-Rayes (2011)), ant colony (e.g., by Lam et al. (2006) and Ning et al. (2011)) and Particle Swarm Optimization (e.g., by Zhang and Wang (2008) and Benjaoran, V., and Peansupap, V. (2020)), were used for the layout optimization.

Most of prior studies solely focused on locating facilities and overlooked sizing facilities. Elbeltagi and Hegazy (2001), Zouein and Tommelein (2001) and Said and El-Rayes (2011) are among the few studies that addressed facility size in site layout planning. However, these studies dismissed the dynamic and uncertain nature of construction operations in their models, which can be sophisticatedly modeled by simulation. Overlooking such important factors lead to inefficiency of site layout in practice. Simulation can address certain drawbacks by modeling uncertainties in construction processes and interactions between facilities. Alanjari et al. (2014) demonstrated the superiority of simulation over SWDF to reduce transportation time in material layout planning. They demonstrated that resource interaction, an important factor, is ignored in SWDF; however, simulation can consider modeling the material handling process to plan efficient layouts. For optimizing site layouts, simulation can be integrated with optimization methods.

Azadivar and Wang (2000), Alanjari et al. (2015) and RazaviAlavi and AbouRizk (2017a) integrated simulation with genetic algorithm (GA) for facility layout planning in the manufacturing industry, material layout planning, and construction site layout planning, respectively. Additionally, simulation can model facility size and space as a resource. RazaviAlavi and AbouRizk (2015) demonstrated simulation capabilities in quantifying the impact of facility size on the project cost by modeling material flow and its inherent uncertainties.

For tunneling projects, simulation has been widely used to model, plan, and estimate the time and cost of the projects. This is due to the repetitive nature of tunnel construction activities and the inherent uncertainties, such as the soil type and equipment reliabilities. Touran and Asai (1987) and Tanaka (1993) were among the first to simulate the tunneling process. Within recent years, different aspects of tunnel projects were incorporated into simulation models. For instance, Frough et al. (2019) used simulation to predict TBM utilization factor and advance rate. Similarly, Likhitruangsilp and Ioannou (2003) developed a simulation-based stochastic model for estimating time and cost performance of tunnel projects. Ruwanpura and AbouRizk (2001) utilized simulation to predict the soil transition in tunneling. Marzouk et al. (2010), Dang (2013) and Moharrami et al. (2021) employed simulation techniques for construction planning of micro tunneling projects.

Despite the evident advantages of simulation in site layout planning, its maximum potential has not yet been employed within this domain. Aleisa and Lin (2005) believe that two schools of thought, “layout then simulation” and “simulation then layout,” have been followed for using simulation in site layout planning. Both approaches isolate the decision-making process of construction planning parameters from site layout parameters—although such parameters have mutual impacts. For tunnel projects, Scheffer et al. (2014) highlighted the significance of the mutual effects of TBM advance rate process, job site layout planning and supply chain management, which were disregarded in most simulation models. Considering the reciprocal effects brings about a novel approach which enables the planner to make decisions concerning their variables through a unified simulation model. Accordingly, simulation is an appropriate method to provide an integrated environment for modeling purposes. RazaviAlavi and AbouRizk (2017b) attempted to develop a generic framework to optimize site layout and construction plan simultaneously while using an integrated simulation-GA model. Despite its novelty, integrating stochastic simulation model with optimization is time consuming and computationally expensive, thus limiting its applicability. Following this research, they developed a generic simulation tool for capturing the mutual impacts of site layout and construction plan (RazaviAlavi and AbouRizk 2021). They demonstrated the effectiveness of integrating site layout planning and construction planning to reduce project costs. However, using this tool requires simulation knowledge, and programming skills, especially for certain complex situations. Scheffer et al. (2016) significantly contributed to this area, by combining discrete event simulation and system dynamics for integrating production and jobsite logistics for tunneling projects. They devised configurable simulation components for construction equipment, storage spaces and production material. Despite their contribution, the site layout components disregarded the site layout constraints, such as the closeness constraints and the safety constraints. Zhou et al. (2009) modeled the closeness constraints using the SWDF method and attempted to find the optimum layout for tunneling projects. They used simulation to examine the efficiency of the enhanced layout by the optimization. However, their model did not consider the influence of the material storage size on the project time, which is a factor deemed as relevant by Ebrahimy et al. (2011a). Ebrahimy et al. (2011a) modeled supply chain management in tunneling by using simulation and substantiated size of the segment storage area as one of main factors affecting the project time.

As previously mentioned, simulation knowledge is limited among practitioners because developing simulation models would require knowledge regarding the technical domain of the real system, simulation modeling techniques and computer programming (Mohamed and AbouRizk 2006). To overcome such challenges, SPS has been developed to facilitate building simulation models for users, even those with limited simulation knowledge, and promote the application of simulation within the industry. In the past, SPS has been customized for varying types of construction projects, such as earth moving (Hajjar and AbouRizk 1996; Siadat and Ruwanpura 2013), aggregate production plants (Hajjar and AbouRizk 1998), construction site dewatering (Hajjar et al. 1998), supply chain (Petrovic 2001; Ebrahimy et al. 2011b), industrial fabrication (Sadeghi and Robinson Fayek 2008), construction noise prediction (Gannoruwa and Ruwanpura 2007), and bridge construction (Marzouk et al. 2008).

For simulating typical tunneling projects, an SPS tool was developed (AbouRizk et al. 1999) using the Simphony (Hajjar and AbouRizk 1996) platform. The current updated version of this tool has been developed in Simphony.NET 4.0 with certain modifications. The overview for the tool is presented in

Figure 1. This tool models three main activities: working shaft and retrieval shaft construction, tail tunnel and undercut construction, and tunnel construction. For additional details on simulating tunnel construction, refer to Ruwanpura et al. (2001). The DST tool proposed in the study was built upon the existing version of the SPS tunnelling tool in Simphony.

To concise, the existing simulation tools for site layout planning of tunnel projects either lack site layout components or do not have sufficient detail for layout planning. Furthermore, most of the existing studies within this field hinder users with limited simulation knowledge from using the tools. The current study strives to develop a simulation-based DST for tunnel site layout planning, which addresses the previously experienced shortcomings. Details of the DST development are described in the following sections.

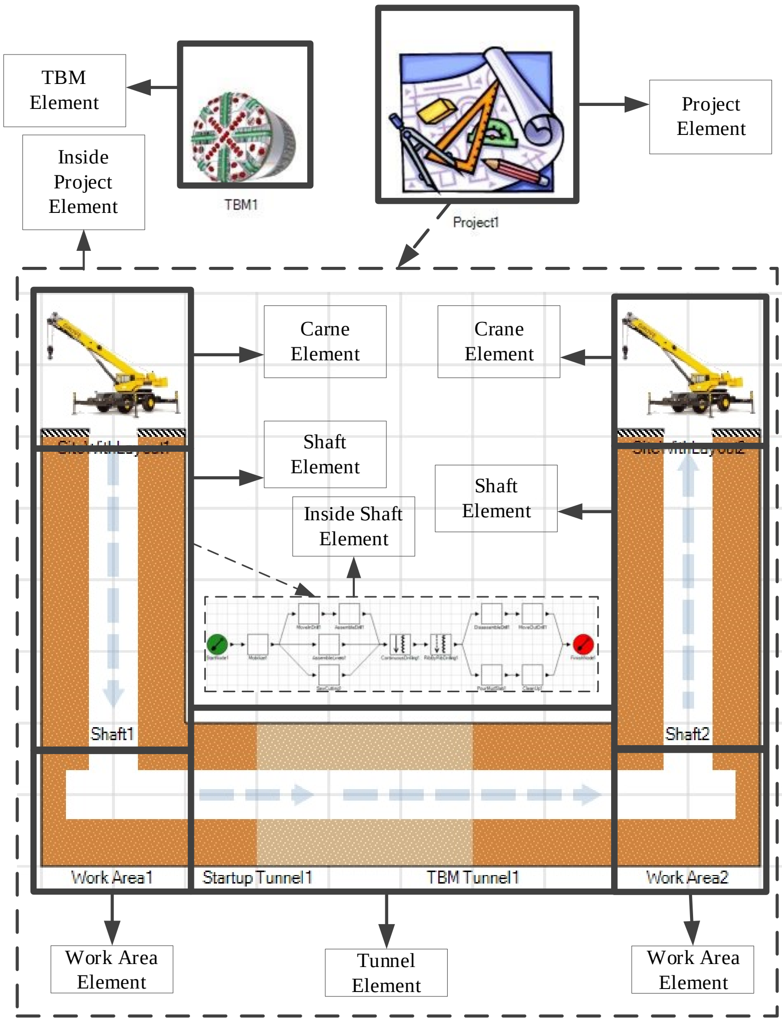


Figure 1: Overview of the Tunneling SPS Tool

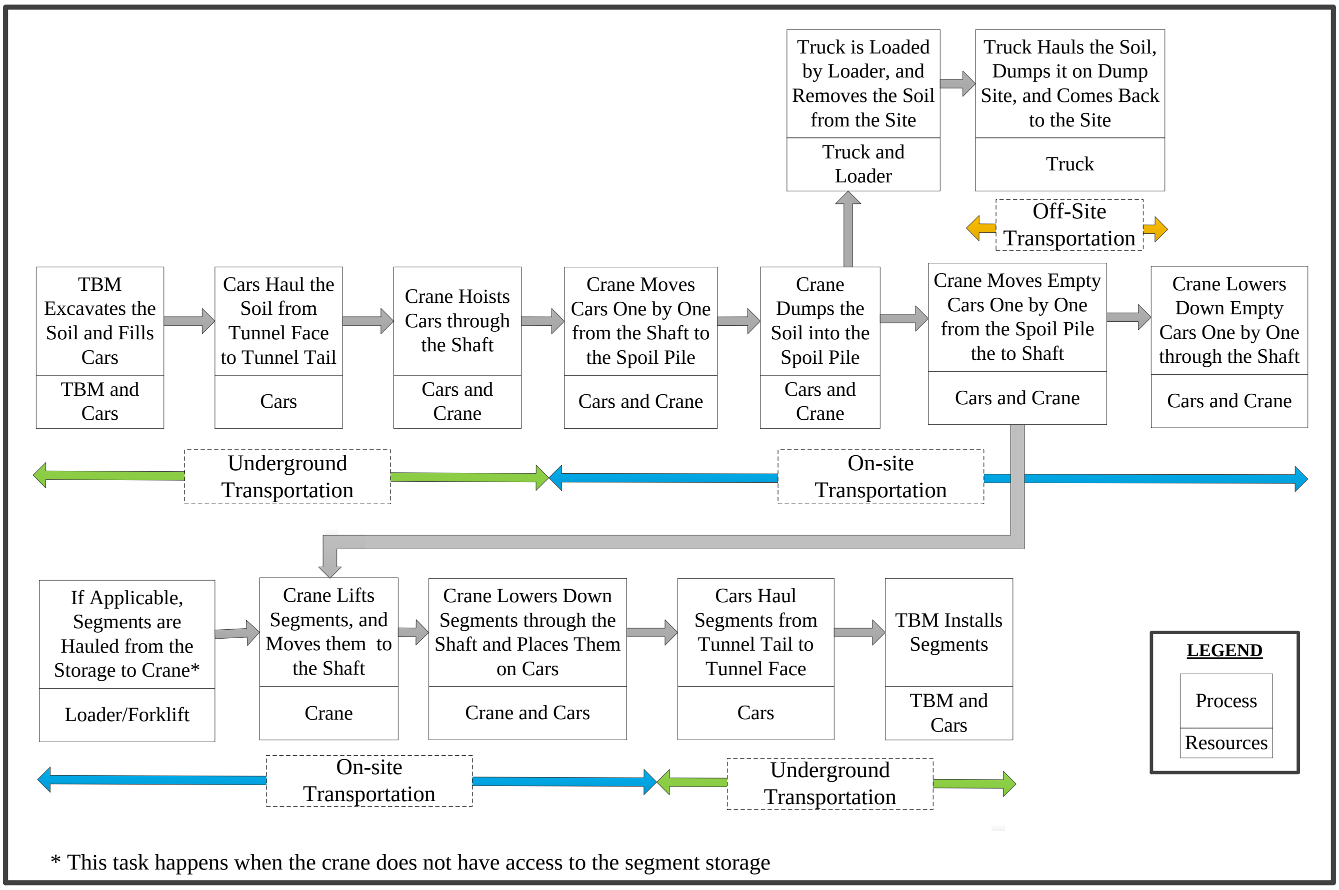
3. Research Methodology

Researchers developed a similar structured framework for building simulation models and tools, whereas, the terminologies and subsequent definitions that they used were slightly different. This research followed the steps proposed by Chwif et al. (2013): 1) Conceptualization, 2) Programming, and 3) Analysis. In the conceptualization stage, the abstract and conceptual models are to be developed. In the abstract model, the product that has to be built is specified (AbouRizk 2010). The abstract model is the "model that is in the mind of the analyst" (Chwif et al., 2013). For the conceptual model, the abstract model is presented explicitly employing text and diagrams (Chwif et al., 2013). This model identifies the processes, resources, environment, and other requirements to build the product (AbouRizk 2010). The next step is programming, in which the computational model is created using a simulator or a simulation language (Chwif et al., 2013). This stage is followed by the analysis phase where the operational model is experimented with, and the results are passed through a verification and validation processes (Chwif et al., 2013). The following sections outline the relevant details pertinent to each step required for the development of the proposed simulation tool.

4. Conceptualization

To develop the abstract model, the intent and specifications of the tool were identified. As previously stated, the proposed tool intended to model the tunnel site layout with sufficient detail along with pertinent parameters from different disciplines, such as material procurement and logistics. This tool was required to be in the form of an SPS tool to further promote its application in the industry. The authors reviewed the literature, observed different tunnel construction sites, and discussed the construction operation details with industry practitioners to develop the conceptual model. This process provided a comprehensive understanding of the site layout requirements and constraints in tunneling projects. In addition, flowcharts and causal loop diagrams were used to identify the tunneling operation and analyze the interdependency of the factors, as well as any possible variable influencing the efficiency of the tunnel site layout. The remainder of this section provides a summary of the conceptualization process.

Within tunnel construction, the TBM excavates the underground soil and fills the muck cars with the soil. The train transports the soil to the working shaft, and typically, a crane hoists the cars to empty them in the spoil pile. The cranes, then, loads the cars with concrete segments to be transported to the TBM for the next cycle. Meanwhile, lining the tunnel, resetting the TBM, surveying, and rail track extensions can be performed in the tunnel. If the empty cars and the segments are unavailable at the tunnel face for the next cycle, the TBM cannot start excavation, which delays the project. Figure 2 illustrates the typical tunneling operations and material transportation processes under the ground and on the surface (on-site and off-site).



* This task happens when the crane does not have access to the segment storage

Figure 2: Soil and segment flows

In site layout planning, three temporary facilities' attributes, type, size, and location, are determined. In tunneling projects, the variety of facilities includes, but are not limited to, the shaft, hoisting equipment (e.g., crane), the spoil pile, the segment storage area, the crew trailer (office), and the electrical facilities for supporting the TBM. Among these facilities, the size of the shaft, hoisting equipment, crew trailer and electrical facilities are fixed and predetermined. In contrast, the size of the spoil pile and segment storage area is variable in nature and is determined based on the quantity of the soil and segment flows.

To illustrate the flow of these materials and their influencing factors, as well as the effect of spoil pile and segment storage sizes on the construction processes, a causal loop diagram is used. In this diagram, arrows link independent variables to dependent variables and polarities of the arrows (positive or negative) demonstrate how changes in the independent variable affect the dependent variables (Sterman, 2000). In the soil flow diagram exhibited in Figure 3 (a), the soil volume in the spoil pile is the primary variable that should be quantified for sizing the spoil pile. TBM production rate, and capacity and the number of trucks deployed for removing the soil from the site are the parameters that can influence the soil flow. Spoil pile size can also affect the soil flow as lack of space in the spoil pile halts the excavation until the soil is removed from the site and enough space is available in the spoil pile, resulting in schedule overruns.

For concrete segment flow shown in Figure 3 (b), the number of segments available in the storage is the primary variable that should be identified for sizing the segment storage. The TBM excavation rate, size of the incoming segment batches, and their inter-arrival time influence the segmented flow. For instance, small incoming segment batches or less frequent segment delivery increases the risk of segment stock-out, which halts the tunneling advancement; this is because the TBM cannot progress without lining. Lack of space in the segment storage can result in additional costs as the site manager would decide to provide off-site segment storage for storing additional segments or postpone the segment delivery—both of which could result in an extra financial burden to the project.

Figure 3(a) and 3(b) displays the complexity and interdependency of the influencing factors in tunneling material flow, as displayed in Figure 3(c). Furthermore, Figure 3(c) shows that these factors are pertinent to different planning disciplines, including site layout, tunneling operations, logistics and material procurement. Each factor and their complex interdependency can be sophisticatedly modeled in an integrated simulation environment to quantify their impacts on the project time and cost. Simulation can also quantify the impact of the location of the facilities (i.e., shaft, crane, spoil pile, and segment storage), which can affect the tunneling production rate. The following sub-section discusses the constraints for positioning facilities.

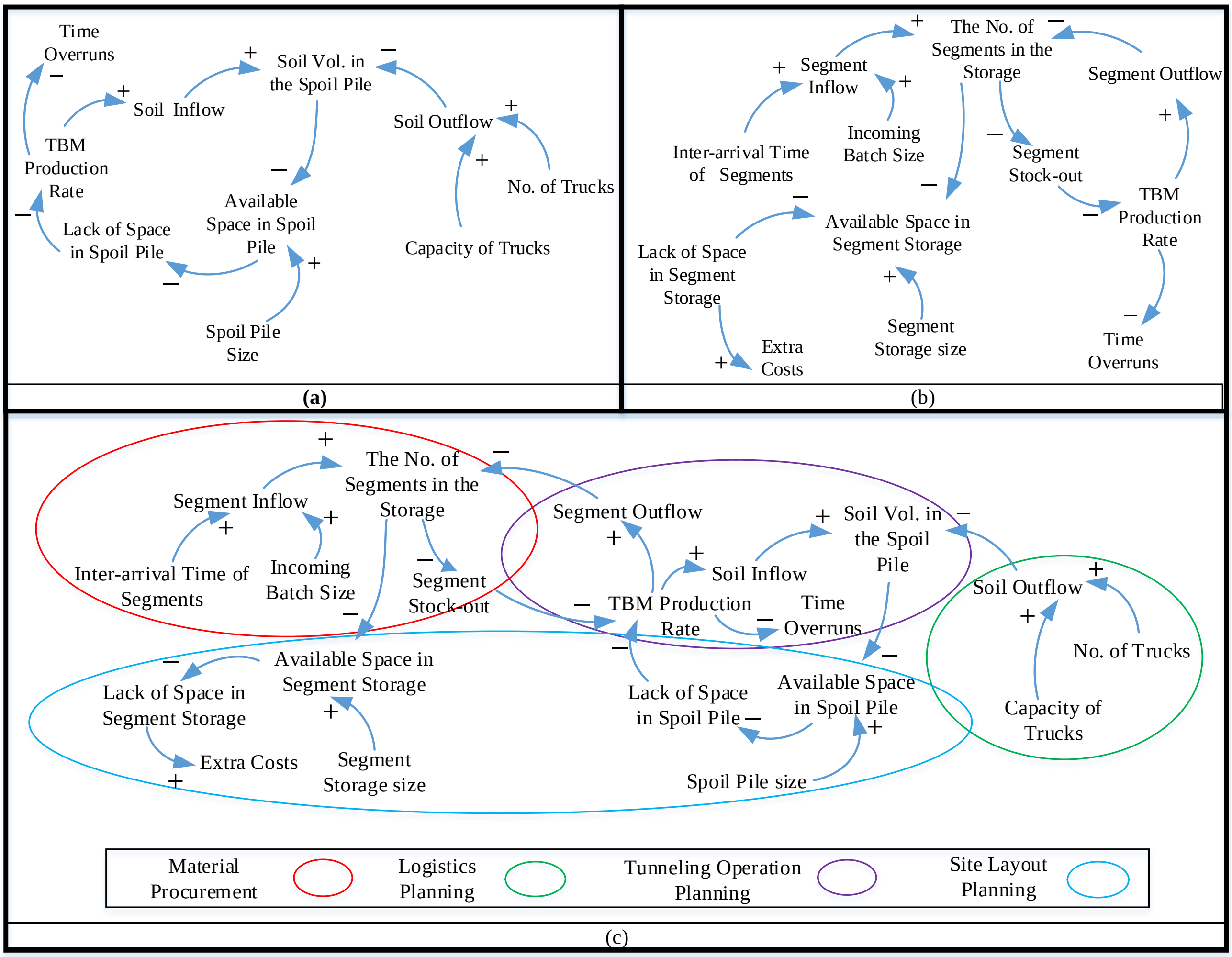


Figure 3 (a): Soil Flow and its Influencing Factors, (b): Concrete Segment Flow and its Influencing Factors, and (c): Integration of Soil Flow and Concrete Segment Flow

4.1. Constraints for Positioning Facilities

In addition to on-site transportation time, there are other constraints such as safety, crane operation, accessibility, and the planner's preferences exist for positioning facilities. For instance, the crew trailer should be located far from the crane due to safety risks of falling objects; the crane should have access to the spoil pile to offload the soil, and no facility should block the access road. These constraints can be defined by the planner through the following rules:

- Minimum distance between facilities: This constraint implies that there must be a minimum distance between two facilities, predominantly for safety purposes.
- Maximum distance between facilities: This constraint implies that two facilities must be positioned within a maximum distance, which can be used for considering crane operation.

- Being inside an area: This constraint implies that a facility should be positioned inside a specific area, which can be used for defining the planner's preferences.
- Being outside an area: This constraint implies that a facility should be positioned outside a specific area, which can be used to identify roads that must not be blocked.

For measuring distance, different methods have been highlighted in developed DST to define various types of constraints—as shown in Figure 4. The application of such distance measurement methods are further discussed in the Case Study section. Two general constraints exist for all facilities: 1) they should be located inside the site boundaries and 2) they should not overlap with one another. These two general constraints are predefined in the model.

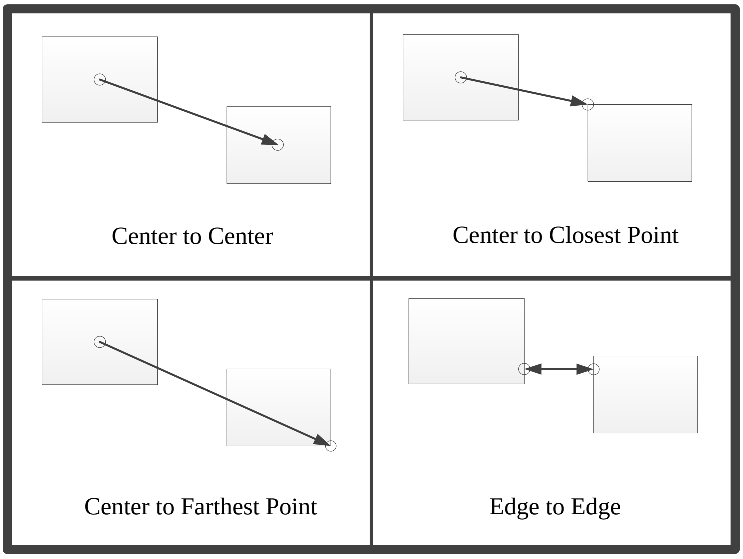


Figure 4: Different Methods for Measuring Distance

5. Programming

For programming DST, the Simphony platform and C# programming language were used. The site layout elements were nested in the existing tunneling SPS tool. Initially, the elements for visualizing the site layout were created, after which the simulation functionality was developed and linked to the existing SPS tool. The developed site layout includes, an element identifying the site area, and the facility elements, which represent different facilities on the site. Facility elements are dragged and dropped onto the site element and are movable. As discussed earlier, the positions of four facilities (i.e., shaft, crane, spoil pile and segment storage), and the size of the spoil pile and segment storage contribute to the production rate of tunneling. Hence, these facilities have predefined elements with specific functionalities in the simulation model. Other facilities that do not have simulation roles (e.g., a tool crib and electrical facilities) use a common element, referred to as the "miscellaneous facility."

Table I shows the main properties that should be specified by the user. The site element that provides an area for creating the site boundaries has a rectangular shape and its size is defined by the width and length of the rectangle. While the sites boundaries are defined by identifying the coordinates of the corner points of the boundary, which are linearly connected. For the facility elements, rectangle is the default shape with an exception for the shaft that can possess a circular shape. The user can identify the location of the facilities either by moving the element on the site, or by entering the coordinates of the reference point of the facility. Furthermore, the orientation of the facility can be changed in the tool—for crane, segment storage and spoil pile, which have simulation roles, specific properties pertaining to the simulation model are defined.

Table I: Main Properties of Site Layout Elements

Element	**Properties**
Site	Site area dimensions, site boundary coordinates, and scale
Shaft	Size, shape, location, and orientation
Crane	Size, location, orientation, durations of hosting and lowering down cars/segments, unloading muck cars, loading segment, and material transportation speed
Spoil pile	Size, location, orientation, capacity, initial volume of soil, truck capacities, truck loading duration, total duration for the trucks to offload the soil on a dump site, costs of equipment (i.e., trucks and loader), and truck reliability
Segment storage	Size, location, orientation, capacity, initial number of segments, size and inter-arrival of segment delivery, segment procurement cost, costs pertaining to extra segments, and the probability (risk) and amount of segment delivery delay
Miscellaneous facilities	Size, location, orientation
Constraints	Distance constraints, and inclusion and exclusion constraints
Area	Coordinates of the corner points

In the DST, to examine whether the planned parameters of the spoil pile and segment storage have significant impacts on the tunneling operation time and cost, the user has the an option to select the capacity of these facilities as unlimited and having all required segments available on the site.

The site layout constraints for positioning facilities can be defined through the “constraints” element. The minimum and maximum distance between facilities are defined by the distance constraint property of the element. Inclusion in, or exclusion from an area can also be defined in this element by determining the coordinates of the corner points. The facilities that should be included in, or excluded from those areas are specified in the “constraints” element. Before running the model, the automatic constraint check is performed to examine whether the inputs are correct and sufficient for running the simulation model. This feature enables the planner to automatically check all the site layout constraints including:

- Existence of shaft, crane, spoil pile and segment storage on the site,
- Being inside the site boundary constraints of facilities,
- Non-overlapping constraints of facilities, and
- Satisfying the site layout constraints defined by the user.

DST provides planners with comprehensive result reports, including tables and charts that intuitively give perceptions about the main parameters measured in simulation and help them make decisions on the modeled variables. This model can stochastically estimate the cost and time for the project, as the major decision-making factors by running Monte Carlo simulation. It is noteworthy that stochastic input data can be utilized by selecting diverse types of probabilistic distributions, available in the DST. Table II presents a summary of the simulation tool outputs. An overview of the tool and samples of these reports are demonstrated in the following section.

Table II: Site Layout Tool Outputs

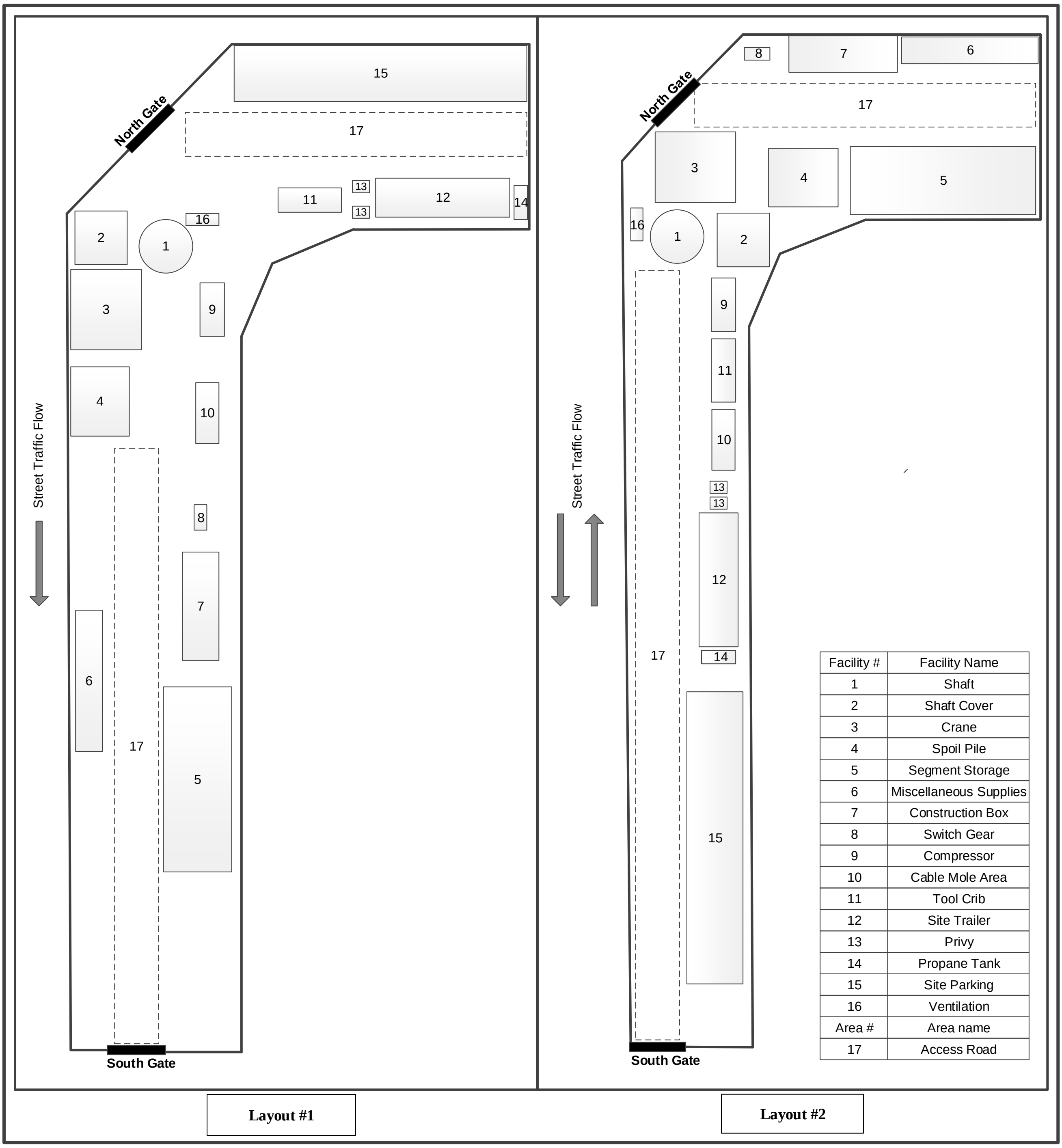
Output data	**Data format**
Cost reports for delivery and storing segments	Table
Cost reports for deployed equipment including the trucks	Table
Details of total project cost and time	Table
Project delays caused by lack of space in spoil pile	Chart and Table
Project delays caused by segment stock-out	Chart and Table
Fullness of spoil pile and segment storage	Chart and Table
Crane utilization	Chart and Table
Truck idle time caused by unavailability of soil	Chart and Table

6. Case Study and Analysis

For the analysis phase, several fictitious scenarios were modeled to experiment the functionality and capabilities of the tool. In addition, the developed DST was used in the layout planning of an actual tunneling project in Canada, as a case study to demonstrate its capabilities and practicality. The tool and the results were presented to the industry practitioners to ensure that it is initiative and easy-to-use. The results of these experiments passed through the verification and validation process.

The case study project took place in a downtown location where the site area occupied a street that had relatively high traffic flow; consequently, the size of the site was a concern for the planner. In this project, the primary objective was to study the impact of two different layouts developed by planners on the production rate of the tunneling operation. Additionally, the authors' interest was to study additional scenarios to demonstrate the capabilities of the DST in the planning phase. Due to confidentiality, normalized data are presented in this paper.

The layouts to be compared are depicted in Figure 5 as Layout #1 and Layout #2. As evident, Layout #2 is narrower than Layout #1, which implies less interference with the street traffic flow. Additionally, the locations of the spoil pile and segment storage are closer to the shaft in Layout #2, which can potentially increase the production rate by reducing on-site transportation time. However, there were other factors (e.g., less congested site and easier access to the site for the trucks and segment trailers from the south gate than the north gate) that led planners to advocate for Layout #1. Therefore, quantitative analysis of the layout impacts on the production rate was helpful for the planners in decision making.



Facility #	Facility Name
1	Shaft
2	Shaft Cover
3	Crane
4	Spoil Pile
5	Segment Storage
6	Miscellaneous Supplies
7	Construction Box
8	Switch Gear
9	Compressor
10	Cable Mole Area
11	Tool Crib
12	Site Trailer
13	Privy
14	Propane Tank
15	Site Parking
16	Ventilation
Area #	Area name
17	Access Road

Figure 5: Layout #1 and #2

In the original plan for tunneling, the planners decided to deploy two trains for transporting soil and segments in the tunnel. This decision would mitigate the effect of on-site transportation on the tunneling production rate since the second train would serve the TBM once the first one is engaged in offloading the soil and loading the segments. To illustrate this decision, the scenarios in which only one train is deployed are also examined. The assumption is to have unlimited capacity for the spoil pile and segment storage and having all the segments ready on the site. This assumption was made since the size of the spoil pile and segment storage is identical in both layouts, and the objective was to evaluate the impact of facility locations on the production rate. Two configurations were built in the DST with the following hard constraints:

- The distance between the center of the crane and the center of the shaft must be less than the jib length of the crane as the crane must have access to the shaft,
- The distance between the center of the crane and the farthest point of the spoil pile must be less than the jib length of the crane as the crane must have access to the entire area of the spoil pile,
- The distance between the center of the crane and the closest point of the site trailer must be more than the jib length of the crane as the trailer must be protected from possible falling objects, and
- All the facilities must be excluded from the access road areas.

Table III shows the specifications of the examined scenarios and their average production rate. As seen in Table III, Scenario A and Scenario B, with two trains and different layouts, have a similar production rate, as the decision to deploy two trains could completely mitigate the impact of the on-site transportation. On the other hand, Scenario C and Scenario D have lower production rates. Comparing Scenario A with Scenario C and Scenario B with Scenario D confirms that deploying one train reduces the production rate by 15% and 13%, respectively. However, deploying the second train increases the mobilization cost. Comparing Scenario C with Scenario D shows that the production rate of Scenario D, in which the spoil pile and segment storage are closer to the shaft, is 2% more than that of Scenario C. That is, Layout B reduces the tunneling time by 2% when one train is used. This comparison demonstrates that the location of facilities in tunnelling projects is significant.

Table III: Examined scenarios and the results in the first stage of the study (presented production rate data are normalized)

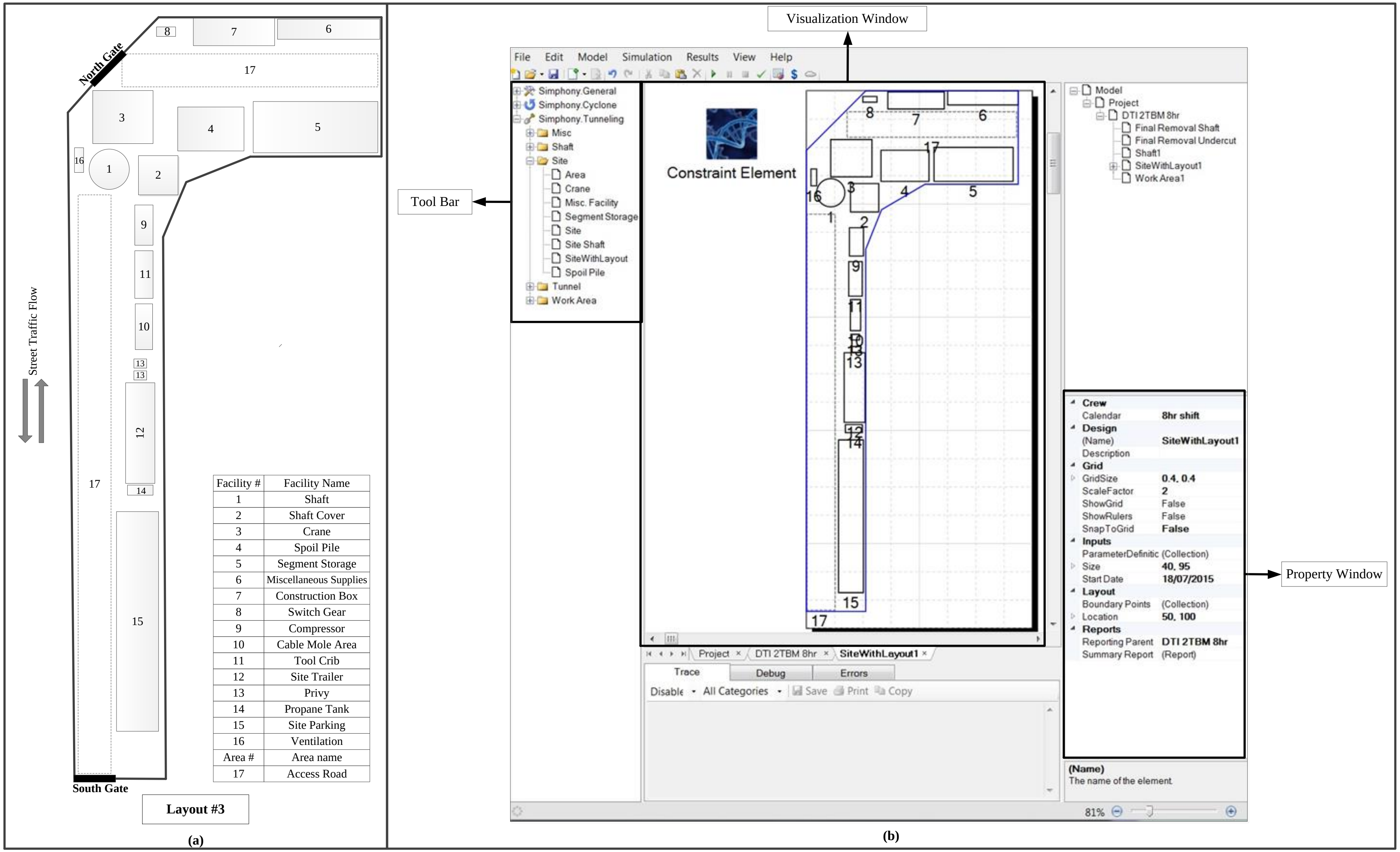
Scenario Name	**Layout #**	**Number of Deployed Trains**	**Tunneling Production Rate (m/day)[1]**
Scenario A	Layout #1	2	3.27
Scenario B	Layout #2	2	3.27
Scenario C	Layout #1	1	2.75
Scenario D	Layout #2	1	2.81

Additionally, the authors were interested in modeling the scenarios with limited capacity for spoil pile and segment storage considering different trucks and segment delivery plans. To demonstrate the impact of facility size on the project time and cost, Layout #3, depicted in Figure 6 (a), was developed, and compared with Layout #2. In Layout #3, the spoil pile is larger, which resulted in a smaller segment storage. In this stage of the study, Layout #2, and Layout #3, along with two types of trucks and two plans for segment delivery, were considered. Table IV gives the specifications of the examined scenarios. To address uncertainties in logistics and segment procurement, the truck travel time was estimated stochastically, and the probability of segment delivery delay was modeled as 10% for 1 to 2 days. For the costs, the following assumptions were made:

- Time dependent costs and time-independent costs for extra segments were considered at 5 $/day and 20 $/day, respectively, per segment.
- Each segment delivery has a fixed cost of $900. Therefore, a lower number of segments in each delivery incurs more delivery costs.
- For truck deployment, the small truck and large truck have 120 $/hr and 140 $/hr costs, respectively. Figure 6 (b) exhibits an overview of the DST in which Layout #3 was created.

Table IV: Examined Scenarios in the Second Stage of the Study

Scenario #	Layout #	Spoil Pile Capacity (m3)	Truck Capacity (m3)	Segment Storage Capacity (# of Segments)	Segment Delivery (# of Segments/Week)
#1	Layout #2	49.5	5	144	48
#2	Layout #2	49.5	5	144	44
#3	Layout #2	49.5	6	144	48
#4	Layout #2	49.5	6	144	44
#5	Layout #3	72	5	120	48
#6	Layout #3	72	5	120	44
#7	Layout #3	72	6	120	48
#8	Layout #3	72	6	120	44



Facility #	Facility Name
1	Shaft
2	Shaft Cover
3	Crane
4	Spoil Pile
5	Segment Storage
6	Miscellaneous Supplies
7	Construction Box
8	Switch Gear
9	Compressor
10	Cable Mole Area
11	Tool Crib
12	Site Trailer
13	Privy
14	Propane Tank
15	Site Parking
16	Ventilation
Area #	Area name
17	Access Road

Crew	
Calendar	8hr shift
Design	
(Name)	SiteWithLayout1
Description	
Grid	
GridSize	0.4, 0.4
ScaleFactor	2
ShowGrid	False
ShowRulers	False
SnapToGrid	False
Inputs	
ParameterDefinitic	(Collection)
Size	40, 95
Start Date	18/07/2015
Layout	
Boundary Points	(Collection)
Location	50, 100
Reports	
Reporting Parent	DTI 2TBM 8hr
Summary Report	(Report)

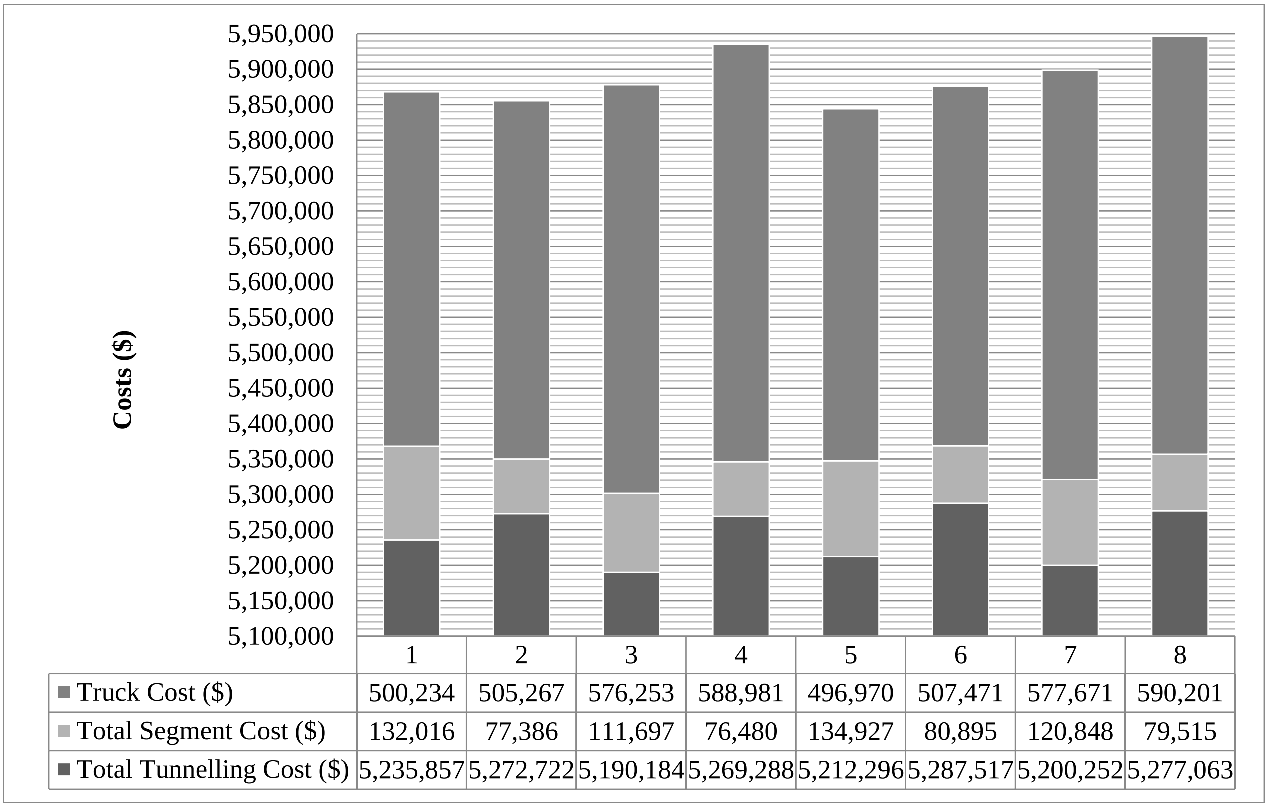
(Name)
The name of the element.

Figure 6 (a): Layout #3, (b): Overview of the DST's user interface

After running Monte Carlo simulation for these scenarios (by running the models 100 times), the stochastic analysis can be undertaken. The average of the results for multiple runs is given in Table V and Figure 7. In Table V, “Spoil Pile Delay” represents the total time that the project was delayed due to lack of space in the spoil pile, and “Segment Delay” means the entire time that the project was delayed due to segment stock-out. In Figure 5, the tunneling cost encompasses labor, equipment, and material costs. The segment costs contain time-dependent and time-independent costs for extra segments and delivery costs.

Table V: Results of the Simulation Model (Presented Data are Normalized)

Scenario #	Production Rate (m/day)	Spoil Pile Delay (days)	Segment Delay (days)
#1	2.76	6.7	0.0
#2	2.74	5.4	6.7
#3	2.80	0.0	0.5
#4	2.74	0.0	10.8
#5	2.78	4.1	0.2
#6	2.73	1.8	10.3
#7	2.80	0.0	0.5
#8	2.73	0.0	10.6



	1	2	3	4	5	6	7	8
■ Truck Cost ($)	500,234	505,267	576,253	588,981	496,970	507,471	577,671	590,201
■ Total Segment Cost ($)	132,016	77,386	111,697	76,480	134,927	80,895	120,848	79,515
■ Total Tunnelling Cost ($)	5,235,857	5,272,722	5,190,184	5,269,288	5,212,296	5,287,517	5,200,252	5,277,063

Figure 7: Cost distribution of the project (presented data are normalized)

As seen in Table V, spoil pile delay for the scenarios with the larger truck (i.e., #3, #4, #7 and #8) is 0, and the segment delay for the scenarios with the larger segment delivery batch (i.e., #1, #3, #5 and #7) is 0 or close to 0. As a result, Scenarios #3 and #7 with the larger truck and larger segment delivery batch have the highest production rate (2.80 m/day). This number is very close to the production rate of Scenario D (2.81 m/day), which was modeled with Layout #2, and experienced no delays due to the assumptions of having an unlimited capacity for the spoil pile and all segments available to the project. On the other hand, the lowest production rates are for the scenarios with the smaller batches of segment deliveries (i.e., #2, #4, #6 and #8). In those scenarios, if the smaller truck is deployed (i.e., #2 and #6), a portion of the delay is due to a lack of space in the spoil pile. However, in the scenarios with the larger truck (i.e., #4 and #8), although no delays occurred due to lack of space in the spoil pile, the production rate was not improved because of the segment stock-out. The segment delays for these scenarios were increased, which confirms the importance of making the right decisions on all the dependant variables from different disciplines.

Comparing the project costs in Figure 5 shows that Scenario #5, with a larger spoil pile size, smaller truck, and larger segment delivery batch, has the lowest costs. This is because deploying the larger truck incurs more costs to the project than the cost of short delays caused by lack of space in the spoil pile. In addition, the larger spoil pile size in Layout #3 reduces the influence of deploying the smaller truck, and the larger batch of segment delivery entailed minor segment delays. Moreover, scenarios (#3, #4, #7, and #8) with the larger truck had the highest costs. Among those, the costs of scenarios #4 and #8 with the smaller batches of segment deliveries were higher because they had more tunneling costs due to the segment delays.

The DST can statistically report on the fullness (i.e., the volume of the available soil or the number of available segments) and fullness ratio (i.e., the ratio of the fullness over the capacity) of the spoil pile and segment storage and create charts on the volume of available soil and the number of available segments in storage.

Table VI presents the average fullness ratio for the spoil pile and segment storage for the examined scenarios.

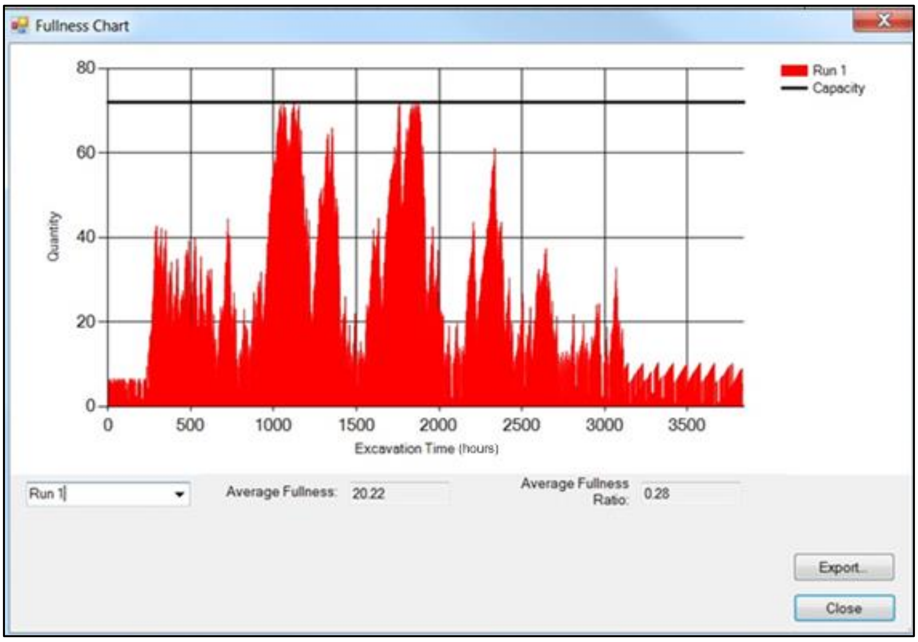
Table VI: Average of fullness ratio for the spoil pile and segment storage

Scenario #	Average Spoil Pile Fullness Ratio	Average Segment Storage Fullness Ratio
#1	0.35	1.35
#2	0.32	0.44
#3	0.13	1.09
#4	0.12	0.39
#5	0.32	1.44
#6	0.24	0.49
#7	0.09	1.28
#8	0.08	0.47

shows a sample of charts for the spoil pile for Scenario #5.

Table VI: Average of fullness ratio for the spoil pile and segment storage

Scenario #	Average Spoil Pile Fullness Ratio	Average Segment Storage Fullness Ratio
#1	0.35	1.35
#2	0.32	0.44
#3	0.13	1.09
#4	0.12	0.39
#5	0.32	1.44
#6	0.24	0.49
#7	0.09	1.28
#8	0.08	0.47



Run 1

Average Fullness: 20.22

Average Fullness Ratio: 0.28

Figure 8: Spoil pile fullness chart for Scenario #5 in 1 run

7. Verification and Validation of the Tool

A few of verification and validation methods described by Sargent (2003) are employed at different stages of the DST development and experiments, summarized as follows:

- **Traces:** For this test, the behaviours of different types of specific entities in the model are traced to determine if the model's logic is correct. The tool has a trace window that can print the time and duration of the activities in the tunnelling operation, the changes occurring in the available number of segments in the segment storage, and the known volume of soil in the spoil pile. This information was analyzed and compared to results from the manual calculation of a model to ensure the model's logic was correct.

- **Parameter variability - sensitivity analysis:** This test is applied to determine whether changing the input values of a model will have the same effect in the model as in the entire system. To perform this test, the importance of size and inter-arrival of segment delivery, the number and sizes of trucks, the capacity of the segment storage and spoil pile, and the locations of facilities are changed. The impacts on project time and cost and the available number of segments in the segment storage, and available volume of the soil in the spoil pile, as applicable, are captured. These impacts and the trends of changes in the model were found to be as what would be expected in the actual system. The results of some of these tests were validated and justified in the case study.
- **Operational graphics:** For this test, values of various performance measures are shown graphically as the model runs through time. To perform this test, values of the available number of segments in the segment storage and the available soil volume in the spoil pile were illustrated graphically in the tool. A combination of this method and the sensitivity analysis was used to capture the impacts of changing the values of some input variables (e.g., size, and inter-arrival of segment delivery, truck capacity) on the available number of segments and the volume of open soil. These impacts and the trends of changes in the model were found to be as what would be expected in the real system.
- **Extreme condition tests**: In this test, the model structure and output are tested to determine their plausibility for any extreme and unlikely combination of levels of factors in the system. To this end, the model was tested for extreme conditions such as having zero capacity for the spoil pile, segment storage, and trucks and having no segment delivery. The outputs were observed to be plausible for these values of inputs, having no production rate. Moreover, considering limitless capacity for the segment storage and spoil pile and enough segments at the beginning of the project yielded the same results as those generated by the model, in which site layout is not modelled by the previous version of the tunnelling SPS tool.

- **Comparison to other models:** For this test, the validated model results are compared to the effects of other (valid) models. A tunnelling operation is modelled using the Simphony General Purpose Template. A model simulating the same tunneling operation was created, and the results were compared. An insignificant discrepancy between the results of the total excavation time (less than 0.1%) was observed, confirming the model's validity.

8. Summary and Conclusion

This paper outlined the development of a simulation-based tool for integrating site layout planning with construction planning of tunneling projects, enabling planners to model the complex dependencies between various variables. In tunnelling projects, overlooking the mutual impacts of the site layout plan and tunneling operation plan can lead to loss of productivity and incurs extra costs. This research shows the significance of modeling site layout variables and construction planning variables in a unified model to find the most efficient plan. An SPS tool was developed to enhance the practicality of the proposed approach in tunnel construction planning, particularly for users with limited simulation knowledge. The comprehensive and intuitive reports of the tool enable planners to simultaneously plan site layout and tunnel construction operations and make informed decisions. Overall, the developed tool is of great assistance to planners to analyze various scenarios and make decisions based on its detailed outputs. The main contribution of this research is to promote simulation application in site layout planning of tunneling projects through the development of a simple-to-use tool, which has sufficient details for site layout planning and considering site layout constraints. The main limitation of the developed tool is lack of optimization capabilities to search for optimum site layout and construction plans. In future research, the tool can be integrated with optimization algorithms to automatically identify optimal solutions. In addition, the proposed approach can be adopted for site layout planning of other construction projects, and similar decision support tools can be produced.

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