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AN INTEGRATED SIMULATION MODEL FOR SITE LAYOUT PLANNING OF TUNNELLING PROJECTS

SeyedReza RazaviAlavi[a], Simaan AbouRizk[b]

[a] Ph.D. Candidate, Dept. of Civil and Environmental Engineering, Univ. of Alberta, Edmonton, Alberta, Canada T6G 2G7.
[b] Professor, Dept. of Civil and Environmental Engineering, Univ. of Alberta, Edmonton, Alberta, Canada T6G 2G7.

[a] reza.razavi@ualberta.ca, [b]abourizk@ualberta.ca

ABSTRACT

Overlooking site layout in the planning phase of construction projects leads to loss of productivity and incurs extra costs. In tunneling projects, site layout has a significant impact on material flow and tunneling operations, particularly on congested sites. In addition, construction planning decisions can influence the efficiency of the layout. This paper proposes simulation as a decision making tool to model tunnel construction operations and site layout, and capture their mutual influences. To facilitate building the simulation model, even for users with limited simulation knowledge, a special purpose simulation (SPS) tool was customized and developed. This simulation tool provides an integrated environment to model the parameters of different disciplines including site layout, material procurement, tunnel operations and logistics. The developed tool is of great assistance for the planners to make decisions simultaneously on site layout and other construction planning parameters, and find the most cost efficient plan.

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

1. INTRODUCTION

Site layout planning, the process of identifying the required type of temporary facilities and determining their size and location, has been studied in the past due to its significant impacts on project productivity, time and cost. Most of these studies, e.g. Zhang and Wang (2008), attempted to improve the location of the facilities by optimizing the sum of weighted distance function ($\sum w \times d$), which strives to minimize transportation cost between facilities. Some studies, e.g. Elbeltagi, et al. (2004), used the same function to subjectively optimize the location of facilities by defining qualitative rates assigned to the interaction and closeness constraints between the facilities.

However, this function does not realistically model the material, workers and equipment flow, and the interaction between facilities. Overlooking these important factors leads to inefficiency of the site layout in practice. Simulation can address this drawback by modeling complex construction processes and interactions between facilities. Alanjari, et al. (2014) proved the superiority of simulation over the sum of weighted distance function (SWDF) to reduce the transportation time in material layout planning. They demonstrated that resource interaction, an important factor, is ignored in SWDF, but simulation can consider it in modeling the material handling process to plan more efficient layouts. Tommelein (1999) developed one of the first simulation-based models for planning the location and the number of tool rooms in construction projects. Azadivar and Wang (2000) integrated simulation with genetic algorithm (GA) for facility layout planning in the manufacturing industry to minimize transportation time. For stock yard layout planning of precast concrete products, Marasini et al. (2001) also used simulation integrated with GA. Simulation was also utilized for sizing temporary facilities in construction site layout planning (RazaviAlavi and AbouRizk, 2014)

Despite the proven advantages of simulation in site layout planning, its full potential has not been employed in 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. The first approach is time efficient and used when the production strategies are predetermined, the stochastic behaviors of the system are insignificant at the early stage of layout planning, and/or the objective is to minimize the travel distance (Aleisa and Lin 2005). The latter approach results in more realistic and efficient layouts to improve throughput levels, and it is more applicable when stochastic demands or complex interactions in the system are significant, operational parameters should be justified prior to layout planning, and/or the objective is minimizing flow congestions (Aleisa and Lin 2005). Both explained approaches isolate decision making on construction planning parameters from site layout parameters while those parameters have mutual

impacts. For instance, when the site is congested and limited space exists for storing materials, material delivery decisions should be made to prevent space shortage on the site. On the other hand, decisions on the number of employed crews can increase the production rate, and consequently the consumption rate of the material, which reduces the need for material storage space (size). These dependencies and mutual impacts bring about a new approach that can integrate construction planning and site layout planning, and simultaneously make decisions on those influencing parameters.

Integrating these parameters is critical in tunneling projects, particularly on congested sites. In tunneling projects, the location of some facilities, e.g. material storage areas, affects material transportation time, which is one of the main drivers of project productivity. In addition, the production rate impacts the size of material storage areas. The limited space for these facilities on tunneling sites can influence construction operation decisions, material procurement and logistic plans. These interdependencies highlight the need to consider all influencing parameters in a unified model. As discussed earlier, simulation can provide this integrated environment for modeling purposes. In this study, a special purpose simulation (SPS) tool is developed to model the tunnel site layout and construction operations, along with the pertinent parameters from different disciplines, such as material procurement and logistics. This tool facilitates the modeling efforts and is able to examine various scenarios and provide users with comprehensive results to make decisions.

In this paper, first, the application of simulation in modeling tunneling projects is described. The significance of tunneling site layout is then analyzed in detail. The developed SPS and its implementation in a case study, followed by a summary and conclusion, are stated in the last sections.

2. SIMULATING TUNNEL CONSTRUCTION PROCESSES

Due to complexity, uncertainties and randomness inherent in construction projects, simulation was found to be an effective tool to model, analyze and improve the performance of construction operations (Mohamed and AbouRizk 2006) and has been used in different sectors of construction projects. CYCLONE (Halpin 1973) was one of the earliest tools developed for simulating construction projects. STROBOSCOPE (Martinez and Ioannou 1994) and Simphony (Hajjar and AbouRizk 1996) are programmable and more flexible simulation tools, primarily used in the last two decades.

Due to the repetitive nature of tunnel construction activities and the inherent uncertainties such as the soil type and equipment reliabilities, simulation has been widely used to model, plan, and estimate the time and cost of tunneling projects. Studies by Touran and Asai (1987), Tanaka (1993) and AbouRizk et al. (1997) were among the first notable attempts to simulate the tunneling process. Different aspects of tunnel projects were incorporated in the simulation model in recent years. Ruwanpura and AbouRizk (2001) tried to predict the soil transition in tunneling. Ebrahimy et al. (2011a) modeled supply chain management in tunneling using simulation. They substantiated that size of the concrete segment storage can affect the project time. Optimizing the closeness constraints using GA, Zhou et al. (2009) tried to find the optimum layout in tunneling projects. They used simulation to examine the efficiency of the enhanced layout from the optimization. Despite the contribution of this research, it did not consider the influence of material storage size on the project time, proven by Ebrahimy et al. (2011a).

Developing simulation models is not a trivial task due to the requirement for knowledge of the technical domain of the real system, simulation modeling techniques and computer programming (Mohamed and AbouRizk 2006). To overcome these challenges, SPS has been developed to facilitate building simulation models and promote the application of simulation in the industry. SPS was customized for different 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 the tunneling process, an SPS tool was developed by (AbouRizk et al. 1999) using the Simphony platform. The current version of this tool has been developed in Simphony.NET 4.0 with some modifications, and designed for modeling projects executed by tunnel boring machines (TBM). This tool can model three main activities: working shaft and retrieval shaft construction, tail tunnel and undercut construction, and tunnel construction. The working shaft is for equipment, crew and segment access and removing the dirt from the tunnel, while the removal shaft is for recovery of the TBM at the end of the tunnel. The shaft can be either circular or rectangular. Excavation and lining are the main activities in shaft construction. Undercut and tail tunnel are located adjacent to the working shaft and retrieval shaft, respectively, for providing more room for moving or setting up equipment. See Zhou et al. (2008) for more information on shaft, tail tunnel and undercut construction. In tunnel construction, the TBM excavates the soil and fills the muck cars with dirt. The cars transport the dirt to the working shaft, and generally a crane hoists the cars to empty them in the spoil pile. Then, the crane loads the cars with the concrete segments to be transported to the TBM for the next cycle. Meanwhile, lining the tunnel, resetting the TBM, surveying, and rail track extensions, when needed, are performed in the tunnel. See Ruwanpura et al. (2001) for further details on simulating tunnel construction.

Figure 1 depicts the overview of the current version of the tunneling SPS tool and its different elements. Each element has its own properties which are the user inputs for specifying the characteristics of the tunnel. Table 1 shows the main inputs of the tool elements. For more flexibility of the tool to model different types of tunnels and activities, some simple elements exist inside of some elements, such as the shaft element that can model the user-defined activities, shown in Figure 1. The graphical interface of this tool is user-friendly and intuitive and a user with limited knowledge of simulation can easily build the model. In the next section, the significance of the site layout plan in a tunneling project is described.
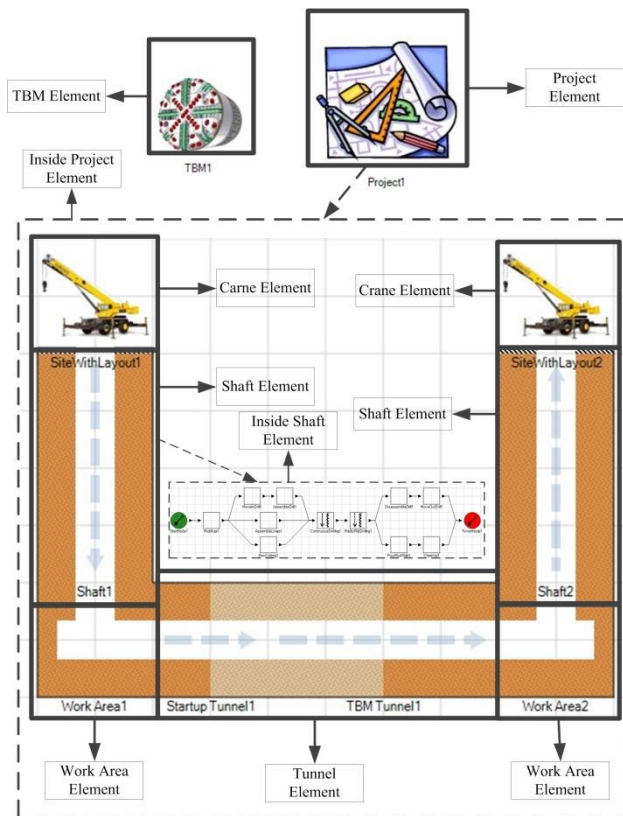

Figure 1: Overview of the Tunneling SPS Tool

Table 1: Tunneling SPS Inputs

Element	Inputs
TBM	Dimensions, resetting duration, and reliability
Crane	Reliability
Shaft	Dimensions and shape, soil spec., and flexible activities for excavation
Work Area	Geometry and dimensions, soil spec., and flexible activities for excavation, train and car spec.
Tunnel	Tunnel length, soil spec., and activity durations and plans

3. THE SIGNIFICANCE OF SITE LAYOUT IN TUNNELING PROJECTS

As discussed earlier, in site layout planning, three attributes of the temporary facilities: type, size and location, are determined. In tunneling projects, the type of facilities include, but are not limited to, the shaft, hoisting equipment (e.g. crane), 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 while the size of the spoil pile and segment storage area is variable and should be determined based on the flow of the dirt and segments, respectively, in the project. To show the flows of these materials and identify their influencing factors, as well as the effect of these facility sizes on construction processes, a causal loop diagram (Sterman 2000) is used. In this diagram, arrows link independent variables to dependent variables and polarities of the arrows (positive or negative) demonstrate how independent variable changes affect the dependent variable (Sterman 2000).

In the dirt flow diagram exhibited in Figure 2, the dirt volume in the spoil pile is the main variable. Since the dirt comes from the TBM excavation, the production rate of the TBM influences the dirt inflow. The dirt is generally removed from the site by trucks. The capacity and the number of the trucks influence the dirt outflow. Since a loader is employed to load the truck, the availability of the loader is another driver of the dirt outflow. The size (capacity) of the spoil determines how much dirt can be stored in it. If the available dirt reaches the capacity of the spoil pile, the dirt can no longer be offloaded in the spoil pile. Consequently, lack of space in the spoil pile halts the excavation until the dirt is removed and enough space is available in the spoil pile.
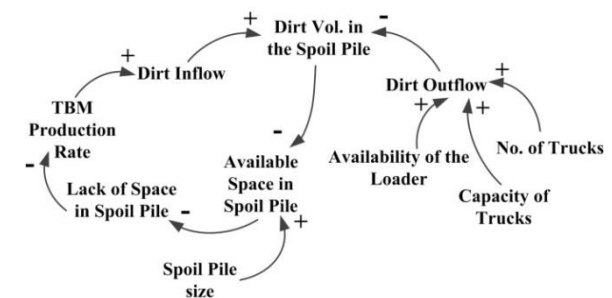
Figure 2: Dirt Flow and its Influencing Factors

For the concrete segment flow shown in Figure 3, the available number of segments in the storage is the main variable. The segments are delivered to the site from a supplier. The size of the incoming segment batches and their inter-arrival time influence the segment inflow. The segments are consumed in lining the tunnel, which depends on the TBM production rate(TBM production rate influences the segment outflow). On the other hand, segment stock-out halts the project because the TBM cannot progress without

lining. The size of the segment storage should be considered in making decisions on the size and frequency of the incoming segment batches. If the capacity of the segment storage is full, no more segments can be delivered to the site. It incurs extra costs to the project to resolve space shortage, for example, by providing an off-site storage or delaying the incoming segment batches.
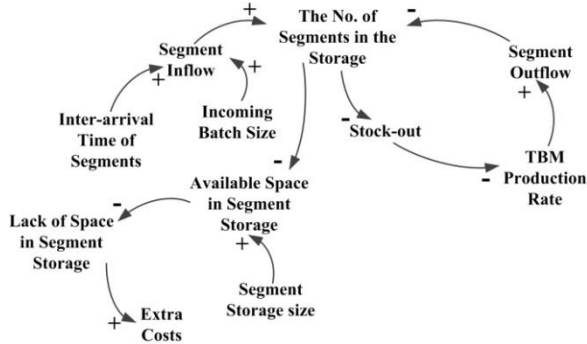

Figure 3: Concrete Segment Flow and its Influencing Factors

Integrating Figure 2 and 3, the complexity and interdependency of the influencing factors in tunneling material flow is observed in Figure 4. It is also seen in Figure 4 that these factors are pertinent to different planning disciplines including site layout, tunneling operations, logistics and material procurement. All these factors and their complex interdependency are sophisticatedly modeled in an integrated simulation environment and their impacts on project cost are estimated.

The location of four facilities: shaft, crane, spoil pile and segment storage, can impact the project time. The closeness of these facilities reduces the transportation time of the dirt and segments. Generally speaking, these durations are more critical in determining the total time of long tunnel construction projects. Thus, it is important to optimally determine where to position these facilities, while the position of the shaft is mostly predetermined on the site. Simulation can measure the effects of these facility positions on the project time and cost. The position of other facilities does not directly affect the project time. Those facilities occupy space on the site, and their positions depend on some closeness constraints or user preferences. For instance, the planners often prefer to position the crew trailer close to the gate, or the closeness constraints specify that the electrical facilities should be close to the shaft. A general constraint for all facilities is that they should be located inside the site boundaries and should not have any overlaps.

It should be emphasized that size and location of some facilities also have mutual influences. The location of the four above-mentioned facilities influences the production rate of the project, which is the main driver of the size of the spoil pile and the segment storage. In addition, in positioning facilities, their sizes should be considered to avoid overlapping of facilities. In particular, on congested sites, the size of

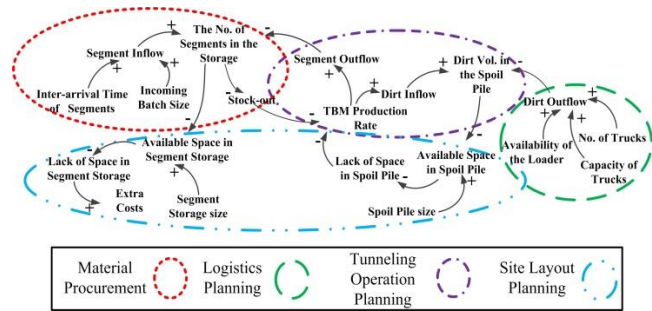the facilities may be adjusted to be fitted for positioning in a certain location.

Figure 4: Integration of Dirt Flow and Concrete Segment Flow

4. SPS FOR TUNNEL SITE LAYOUT PLANNING AND CASE STUDY

The SPS for planning the site layout is developed in Simphony and nested in the current version of the tunneling tool to keep the integrity of the site layout tool with the existing Simphony's tools. The site layout tool includes a site element, of which size should be determined, and the facility elements, which are dragged and dropped to the site, and are movable. As discussed earlier, the positions of four facilities (i.e. shaft, crane, spoil pile and segment storage) and the size of spoil pile and segment storage contribute in simulating projects. That is, these facilities have predefined elements in the tool with specific functionalities. Other facilities, not having any simulation roles (e.g. a crew trailer and electrical facilities), use a unique element: "miscellaneous facility" element. For these facilities, the user should determine only their size and position. Table 2 shows the main properties of these elements. To examine the effect of the designed spoil pile and segment storage size on the project time and cost, the user is given an option to select the capacity of these facilities as unlimited and compare the results with the limited capacity. Ultimately, the integrity check of the model is performed once the user wants to execute it, done manually, or wants to run the model, done automatically. The main items checked through the integrity check process are as follows:

- Existence of shaft, crane, spoil pile and segment storage on the site
- Non-overlapping constraints of facilities
- Being inside the site boundary constraints

This tool provides the user with comprehensive result reports including tables and charts that intuitively give the user perceptions on the main parameters measured in simulation. These reports help the user make decisions on site layout and other parameters. The major decision-making factor for site layout is the project cost, which is also estimated by simulation. This template is capable of analyzing stochastic input data

with diverse types of distributions and running Monte Carlo simulation. The results are accessible for multiple runs in the form of statistical results as well as results for each individual run. Table 3 presents a summary of the simulation tool outputs. An overview of the tool and samples of these reports are demonstrated in a case study.

Table 2: Main Properties of Site Layout Elements

Element	Properties
Site	Dimensions and scale
Shaft	Size, shape and location
Crane	Size, location, loading, unloading and hosting durations, and swing speeds
Spoil pile	Size, location, capacity, initial vol. of dirt, and truck capacities, loading travel durations, and truck and loader costs
Segment storage	Size, location, capacity, initial vol. of Segments, size and inter-arrival of segment delivery, and extra storage costs
Misc. facilities	Size and location

Table 3: Site Layout tool Outputs

Output data	Data format
Equipment, labor, and rental cost report	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
Loader utilization	Chart and Table
Truck idle time caused by unavailability of the loader	Chart and Table
Truck idle time caused by unavailability of the dirt	Chart and Table

5. CASE STUDY

In a tunneling project with a length of 1030 meters, two different layouts: Layout (A) and Layout (B) were designed based on the geometry of the site as illustrated in Figure 5 and 6, respectively. Figure 5 and 6 are the snapshots of the tool user interface depicting an overview of the tool. In Layout (A), the spoil pile size is smaller and its distance to the shaft is slightly more than those of Layout (B). In turn, the size of the segment storage and its distance to the shaft in Layout (B) is more than those of Layout (A). In addition to selection of a suitable layout, decisions should also be made on the size of the trucks deployed for removing the dirt, and the frequency of segment deliveries and quantity of the segments in each delivery. The planner of this project can opt between two types of the trucks with 10 m^3 and 12 m^3 capacity. Choosing the larger truck incurs more hourly costs while reduce the risk of spoil pile fullness. The planner has also two options for supplying

segments: 9 segment batches per day or 16 segment batches per two days (each batch includes 4 segments), which have identical costs. However, if the segment storage does not have enough capacity for storing the incoming segments, they are stored off-site which incurs fixed cost for transportation and daily cost for maintaining that segment batch. As discussed earlier, all these variables are interdependent and can influence each other. That is, this case study aims to determine the most cost efficient plan from the possible scenarios briefly presented in Table 4.

Based on the characteristics of the project, the tunneling process was simulated using the developed tool. The duration of the most activities such as excavation rate, rail tack extension, and surveying was modeled stochastically to account for the project uncertainties. The cost data are also incorporated to evaluate the efficiency of the scenarios. Having run the model for multiple times, it was revealed that scenario #5 has the minimum total cost on average as shown in Figure 7. Figure 7 also shows the cost distribution between tunneling costs including equipment and labor costs for tunnel construction, truck and loader costs for removing the dirt, and extra storage costs for the off-site segment storage if any.

The most cost efficient scenario (#5) is with having large spoil pile size, deploying large truck and ordering segment more frequently. Investigating the results indicates that deploying a small truck (10 m^3) is not efficient whereas the scenarios with the small truck (#3, #4, #7 and #8) have the highest costs. Among these scenarios, the costs of the scenarios with smaller spoil pile size are more. It is because of the fact that the fullness of the spoil pile halts the tunnel construction process, which entails more tunneling costs due to idleness of the resources. Hence, the extra costs of the large truck are compensated by completing the project earlier. These results confirm that the spoil pile size and decisions on the logistics (i.e. truck size) are dependent and have a significant influence on the tunneling project cost. That is, modeling construction process along with site layout and logistics to capture their influences is crucial.

By deploying the large truck, the tunneling process is executed with higher rates, and the demand of the segments becomes more. As a result, more frequent segment deliveries are desirable in this project. Although this decision incurs the extra storage cost, it reduces the risk of segment stock-out, which entails delays in the project. To highlight the importance of this decision, scenario #5 and #6 are compared. All the specifications of these two scenarios are identical except for the segment delivery plan. The results of the model show that the total delay time caused by lack of segments for scenario #5 and #6 are 57 and 289 hours, respectively, which leads to saving $136,507 in scenario #5 comparing with scenario #6.

Similar analysis and comparisons between different aspects of the project performance can be carried out for each scenario using the comprehensive reports of the
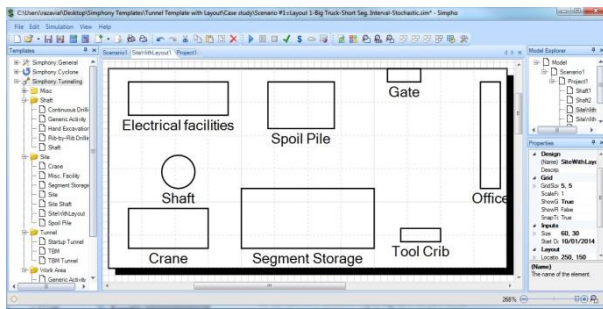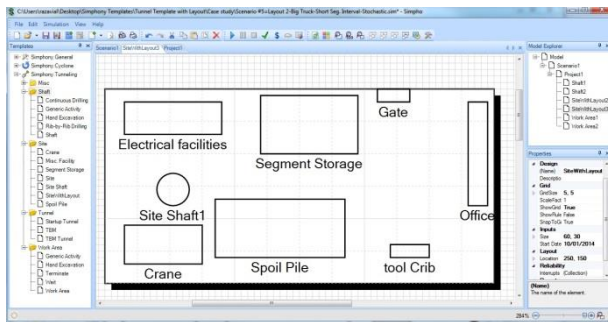
tool.

Figure 5: Layout (A)

Figure 6: Layout (B)

Table 4: Specifications of the examined scenarios

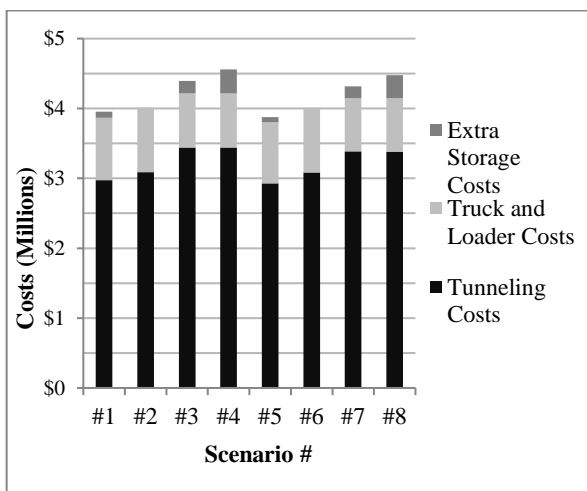| Scenario	Layout type	Segment Delivery	Truck Capacity
#1	A	9/day	12 m3
#2	A	16/2 days	12 m3
#3	A	16/2 days	10 m3
#4	A	9/day	10 m3
#5	B	9/day	12 m3
#6	B	16/2 days	12 m3
#7	B	16/2 days	10 m3
#8	B	9/day	10 m3

Figure 7: Cost results of the examined scenarios

6. SUMMARY AND CONCLUSION

This paper demonstrated the significance of the site layout plan in tunneling projects. The mutual impacts of site layout parameters, i.e. facility size and location, and construction planning parameters from different disciplines were analyzed and modeled through an integrated simulation environment. To promote the practicality of the simulation tool in the industry, a user-friendly SPS tool for tunneling site layout planning was developed. This tool complements the existing tunneling simulation tool, which models only tunnel construction operations.

The result of this research shows that decisions on construction plan, material procurement, logistics and site layout are dependent in tunneling. Ignoring this dependency leads to loss of productivity and inefficiency of the site layout, which further substantiates the merit of the research. The main contribution of this research is to integrate interdependent parameters from different disciplines implementing simulation to obtain the most cost-efficient construction plan for tunneling projects. The comprehensive and intuitive reports of the simulation model on the project cost and project delays along with other aspects of the project performance are of great assistance for planners to make complicated decisions. This approach could also be adopted for site layout planning of other types of construction projects, and similar tools could be produced.

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AUTHOR BIOGRAPHIES

SeyedReza RazaviAlavi is a PhD candidate in Construction Engineering and Management at the University of Alberta. He received his BSc and MSc in Civil Engineering in 2007 and 2010, respectively. His research interests are mainly focused on simulation modeling including discrete event, continuous, and hybrid simulation models, construction site layout planning, and material management.

Simaan AbouRizk holds an NSERC Senior Industrial Research Chair in Construction Engineering and Management at the Department of Civil and Environmental Engineering, University of Alberta, where he is a Professor in the Hole School of Construction Engineering. He received the ASCE Peurifoy Construction Research Award in 2008. He was elected fellow of the Royal Society of Canada in 2013.