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Article

Stochastic Simulation of Construction Methods for Multi-purpose Utility Tunnels

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Abstract: The traditional method of installing underground utilities (e.g., water, sewer, gas pipes, electrical cables) by burying them under roads has been used for decades. However, the repeated excavations related to this method cause problems, such as traffic congestion and business disruption, which can significantly increase financial and social costs. Multi-purpose Utility Tunnels (MUTs) are a good alternative for buried utilities. Although the initial cost of MUTs is higher than that of the traditional method, social cost savings make them more feasible, especially in dense urban areas. Different factors, such as the specifications of utilities, the location of the MUTs, and the construction method, should be investigated to determine if MUTs can be an economical and practical alternative. The construction method is one of the most important factors to assess to have a successful MUT project and reduce its impact on the surrounding area. Simulation can be used to investigate the different construction methods of MUTs. In this paper, two Stochastic Discrete Event Simulation models depicting two MUT construction methods (i.e., microtunneling and cut-and-cover) are developed to analyze the duration and cost of the MUT projects. Also, 4D simulation models of these methods are developed for constructability assessment of these projects.

Keywords: discrete event simulation; Multi-purpose Utility Tunnel; construction methods; microtunneling; cut-and-cover

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1. Introduction

Utility networks are installed above and below ground. The development of utilities above ground, especially in urban areas, has several disadvantages, such as presenting safety hazards, limiting urban spaces, and uglifying urban scenes. Therefore, urban areas often place utilities underground [1]. Reports have stated that underground utilities in developed areas have reached or are nearing the end of their service lives, requiring many repair and replacement projects [2,3]. These projects have caused street closures and traffic disruptions, environmental pollution, etc., in urban areas (i.e., social cost) [4]. As a solution, Multi-purpose Utility Tunnels (MUTs) offer a long-term, sustainable alternative by hosting utilities in a tunnel [5,6]. MUTs are "underground utilidors containing one or more utility systems, permitting the installation, maintenance, and removal of the system without making street cuts or excavations" [7]. MUTs are also called utility corridors, utilidors, common service tunnels, common utility tunnels, and common utility ducts [8].

The traditional method of installing underground utilities (e.g., water, sewer, gas pipes, electrical cables) is burying them under roads. MUTs are more expensive than conventional methods, but they could be more practical in dense areas due to social cost savings [9]. Researchers have suggested using crowdfunding [10] and incentive mechanisms in public–private partnership projects [11] to finance utility tunnels construction projects. To make

MUTs an affordable and efficient alternative to buried utilities, factors such as utility specifications, MUT location [12], and construction method, should be investigated. The construction method is one of the most important factors to assess for a successful MUT project [13].

MUT construction methods can be classified into two main groups: cut-and-cover (C&C) methods [14,15] and trenchless methods [16]. Despite the high initial cost of the trenchless methods, avoiding the excavation of roads and low social costs make these methods more appealing. Also, by using trenchless methods, MUTs can be built under the current utilities; therefore, the removal or diversion of the old utilities during the construction period is not necessary. Further, the C&C method is almost impossible or is more expensive in dense areas, in deep MUT projects, or in some soil conditions (e.g., hard rocks).

Simulation can be used to evaluate construction methods and estimate their duration and cost. Shannon [17] defined it as "the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system". Simulation can also be used for planning and resource allocation, risk analysis, site planning, and productivity measurement [18,19]. Simulation modeling has been used to study, analyze, and plan various types of tunneling projects, such as [20–24]. However, few tunneling studies have used simulation to model C&C [25] and microtunneling [26–30] construction methods. Although simulation has been used for tunneling projects, such as water and metro tunnels, a lack of research on using stochastic simulation for MUT construction to compare the duration and cost of different construction methods remains.

This paper extends our previous work [31] by simulating different construction methods, considering the durations and costs of these methods in a stochastic manner, and developing 4D simulation models. While simulation focuses on the time dimension of a project simulation, 3D models enable architects, engineers, and project managers in the Architecture, Engineering, and Construction (AEC) sector to visualize construction projects in the design phase and detect clashes between components. However, 3D models do not offer scheduling or construction progress control. A 4D model is a 3D model linked to the construction schedule [32]. Four-dimensional models have been used to verify the accuracy of work sequences and schedules and assess site accessibility and spatial-temporal conflicts [33].

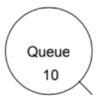
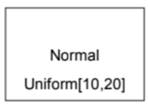
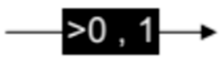
This paper aims to develop detailed Stochastic Discrete Event Simulation (DES) models of two MUT construction methods (i.e., C&C and microtunneling). The objectives are to (1) analyze the durations and costs of the MUT projects using these methods while considering the different soil conditions and tunnel dimensions; (2) compare the two MUT construction methods based on the stochastic results of the DESs; and (3) assess the constructability of the MUT projects using 4D simulation including construction equipment. The rest of the paper is organized as follows: Section 2 presents the materials and methods used in this study, Section 3 presents the results, Section 4 offers a discussion, and Section 5 concludes the findings of the study and identifies opportunities for future work.

2. Materials and Methods

As previously mentioned, one of the most important factors affecting the cost and efficiency of MUT projects is the construction method. When considering which construction method to use, decision makers should take several factors into consideration, such as location (e.g., urban, rural, new development, etc.); soil type; buried underground utilities/structures; depth of the tunnel; the impact of construction on adjacent structures; and social cost [34]. After selecting the location, it will be analyzed for determining different data that could affect the construction method such as soil data (e.g., type of soil, cohesion, underground water).

Stochastic DES is used to model the construction of MUTs using the C&C and slurry microtunneling methods. DES is a simulation method that models the operation of a system as a discrete sequence of events in time [35]. The simulation models are developed using EZStrobe [36]. EZStrobe is a general-purpose simulation system based on activity cycle diagrams. Table 1 lists the EZStrobe elements that are used to create the simulation models. The modeling elements consist of nodes and links. Links are used to connect the network nodes and indicate the direction, quantity, and type of resources that flow through them. The node at the tail of the link is the predecessor and the node at the head is the successor. There are two types of nodes in EZStrobe which are queues and activities. Queues are nodes that hold the resources when they are either stored there or waiting to be used. Each queue is associated with a particular resource type. On the other hand, activities are nodes that represent tasks in which the resources are productive. Resources engaged in an activity stay tied for the duration of the activity. There are two types of activities used in creating the presented simulation models which are the normal and the combi activities. The normal and the combi activities differ in two aspects: the first is the way the activities may start and the second is the way they acquire the resources they need. Combi activities represent tasks that must meet certain conditions in order for them to start. Most of the time, these conditions are related to the availability of resources in the queues preceding that combi. That is, combi activities withdraw the required resources from the preceding queues. Therefore, combi activities can only be preceded by queues because inactive resources reside only in queues. Normal activities, on the other hand, represent tasks that start immediately after other tasks end. Moreover, they acquire the required resources from the preceding task that has just finished.

Table 1. EZStrobe elements used to create the simulation models of the MUT.

Symbol	Description
	Queues hold resources that are idle. Each queue is associated with a particular resource type.
	Combi activities represent tasks that start when certain conditions are met.
	Normal activities represent tasks that start immediately when preceding tasks end.
	Links connect network nodes and indicate the direction and type of resources that flow through them.

Developing simulation models requires not only knowledge of using software but also an understanding of construction processes. The general descriptions of the C&C and microtunneling methods are not covered in this paper, as they are well covered in the literature [25,37–42]. To develop the simulation models of microtunneling and C&C methods, the required activities are determined. Then, the sequence and relationships between different activities, as well as the resources for each of them are defined. The duration and cost of each activity are then defined using a stochastic distribution to study the range of potential durations and costs of the project considering the interactions between the activities.

Four-dimensional simulation models are created to visualize and assess the constructability of the construction methods. These models are created by extracting the durations of activities from the DES and linking them to the corresponding 3D models. The simulation includes the construction equipment, and it analyzes the spatio-temporal conflicts and the impact of the MUT project on the surrounding area. By using stochastic simulation, the probability of potential stochastic spatio-temporal clashes can be calculated [19]. These clashes may happen, for example, in the event of an equipment breakdown, which will delay the installation of new sections, combined with the continuous delivery of sections to the site resulting in a congested site.

2.1. C&C Simulation Model

The process of MUT construction using this method includes (1) surveying; (2) demolition of urban furniture; (3) excavation of the surface for diverting the current utilities; (4) diversion of the old utilities that already exist in the location; (5) trench excavation; (6) assembly of the trench shoring system; (7) preparation of the bed for placing the precast concrete sections; (8) delivery of the precast concrete sections to the construction site; (9) attaching the sections to the crane and lifting them; (10) placement of the sections; (11) sealing the joint between sections; (12) installation of the required supports (e.g., trays and hangers) for the utility systems; (13) installation of the utilities; (14) displacement of the trench shoring system; (15) backfilling; (16) installation of the MUT's own networks (e.g., security cameras, fire detectors, etc.); and (17) pavement restoration.

Figure 1 shows the developed simulation model for this construction method. Table 2 lists the activities' names, descriptions, durations, and costs for this simulation model. The durations and costs used in this paper were adapted from other studies [28,41,43,44]. The process starts with surveying the location of the project. Then, the urban furniture (e.g., benches and light poles) are demolished. Afterward, the excavation of the street's surface in the location of the first segment of the MUT starts and continues until the number of excavation cycles for that segment is achieved. This condition is modeled in Q3 as "NEC1 == NEC1". The number of excavation cycles is calculated using the excavation volume and the trucks' capacity. Once the condition is met, the existing utilities are diverted to start excavating the trench. Similarly, NEC2 is used to control the number of excavation cycles required for the MUT segment. Once the condition is met, the trench shoring system is installed, and the trench bed is constructed to place the sections. The MUT sections are transported to the construction site using a truck, and a crane unloads the truck and places the section in the trench. After being unloaded, the truck returns to bring another section. After the sections are placed in the trench, the joints between them are sealed. Afterwards, the required supports for the utilities are installed and the utility networks are implemented. Finally, the trench shoring system is removed, and the trench is backfilled. These activities will be repeated for each segment. When all of the MUT segments are completely constructed, the networks of the MUT, such as cameras and fire detectors, are implemented in the tunnel and the pavement of the street is restored.

2.2. Microtunneling Simulation Model

The slurry microtunneling method involves two major steps: shaft construction and tunnel construction. In this paper, we use the precast concrete segmental method for building the shafts. In the segmental method, the shaft is constructed by placing the cutting edge and segmental rings on the surface and pushing them into the ground using jacking arms. At the same time, the soil inside the ring is excavated and removed. This process is repeated until the shaft reaches the required depth. The advantages of this method include minimum noise and ground vibration during construction; significantly reduced installation times, as excavation and ring placement can be performed on a continuous cycle; and reduced hazards of underground construction since most work is carried out above ground. Since most recent MUTs are constructed in dense areas, these advantages have increased the use of the segmental method for shaft construction.

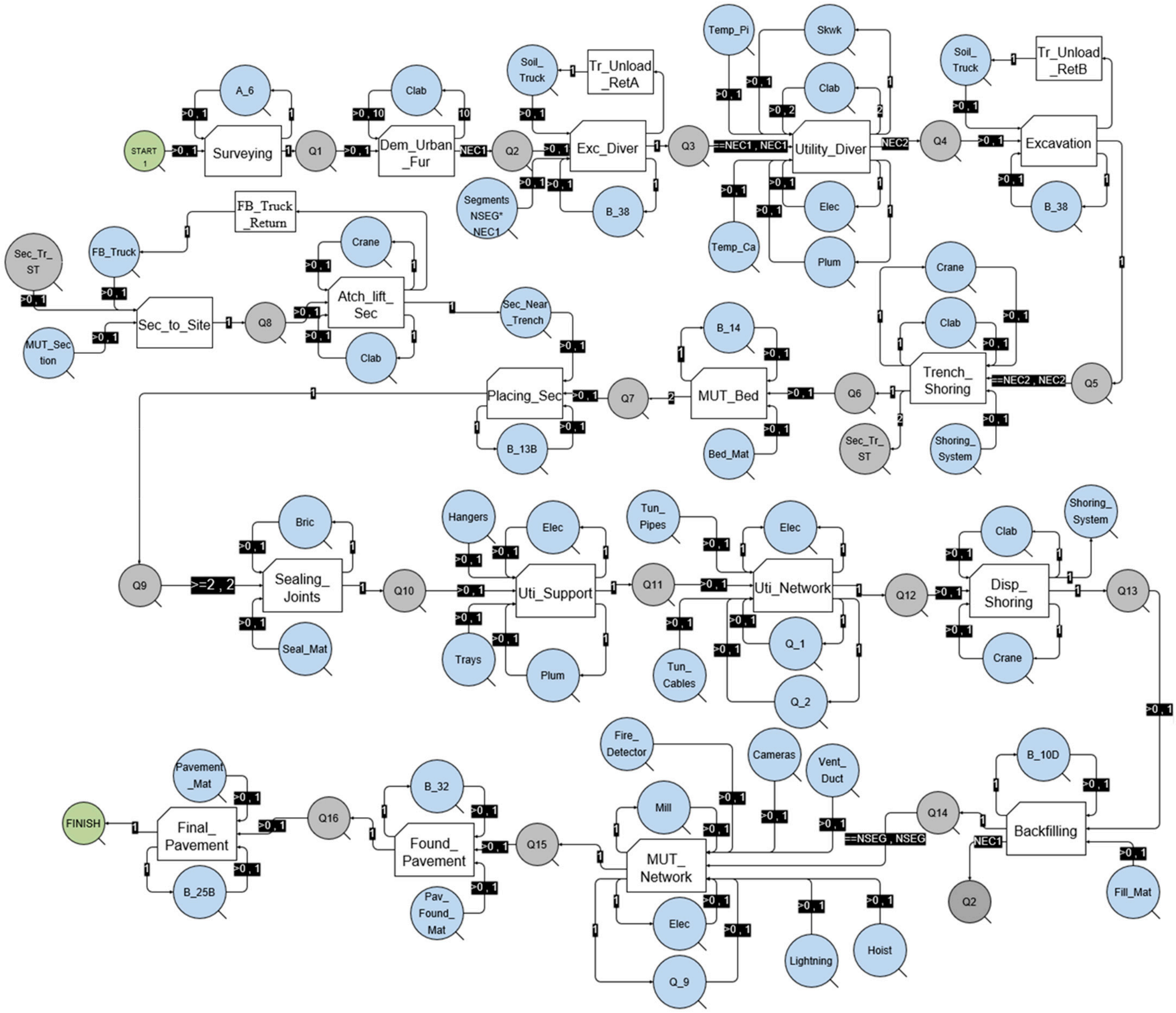


Figure 1. MUT construction sequence using C&C method.

Table 2. Durations and costs of C&C activities.

Activity Name	Activity Description		Duration (min)		Cost (USD/min)	
			3 m Tunnel	4 m Tunnel	3 m Tunnel	4 m Tunnel
Surveying	Surveying		U [120, 180]		U [0.99, 1.83]	
Dem Urban Fur	Demolition of urban furniture		N [4320, 504]		U [7.73, 14.35]	
Exc Diver	Excavation for utility diversion	Fine sand	U [272, 506]	U [327, 607]	U [2.95, 5.45]	
		Sand and gravel	U [372, 690]	U [446, 828]	U [3.00, 5.58]	
		Clay/Marl	U [463, 861]	U [557, 1034]	U [3.18, 5.91]	
Tr Unload RetA	Dump truck cycle		U [40, 80]		U [0.65, 1.21]	
Utility Diver	Diversion of the existing utilities		N [720, 120]		U [8.12, 15.08]	

Table 2. *Cont.*

Activity Name	Activity Description		Duration (min)		Cost (USD/min)	
			3 m Tunnel	4 m Tunnel	3 m Tunnel	4 m Tunnel
Excavation	Trench excavation	Fine sand	U [636, 1182]	U [764, 1420]	U [2.95, 5.45]	
		Sand and gravel	U [867, 1611]	U [1042, 1934]	U [3.00, 5.58]	
		Clay/Marl	U [1083, 2011]	U [1300, 2414]	U [3.18, 5.91]	
Trench Shoring	Assembly of the trench shoring system		U [90, 120]		U [2.55, 4.73]	
MUT Bed	Preparation of the MUT bed		U [39, 73]	U [47, 87]	U [15.74, 29.24]	
Sec to Site	Bringing the sections to the site		U [20, 40]		U [0.32, 0.59]	
FB Truck Return	Flatbed truck returning		U [20, 40]		U [0.32, 0.59]	
Atch lift Sec	Attaching the sections to the crane and lifting		T [1.6, 1.7, 2.3]		The cost of this activity is included in the cost of placing the MUT sections.	
Placing Sec	Placement of the MUT sections		T [2.4, 3.3, 4.5]		U [40.07,74.41]	U [53.42, 99.22]
Sealing Joints	Sealing of the segment joints		U [22, 41]	U [29, 55]	U [1.25, 2.33]	
Uti Support	Installation of the utility supports		U [649.6, 1206]		U [6.98, 12.96]	
Uti Network	Installation of the utility networks		U [817, 1517]		U [37.72, 70.06]	
Disp Shoring	Displacement of the shoring system		U [90, 120]		U [2.55, 4.73]	
Backfilling	Backfilling		U [368, 683]	U [419, 779]	U [4.53, 8.41]	
MUT Network	Installation of the MUT networks		U [8269, 15,357]		U [28.93, 53.73]	
Found Pavement	Construction of the pavement foundation		U [48, 88]	U [57, 107]	U [85.44, 158.68]	
Final Pavement	Final pavement		U [97, 179]	U [116, 216]	U [236.07, 438.41]	

N [a, b]: normal distribution; a is the mean, and b is the standard deviation. T [a, b, c]: triangular distribution; a is the low, b is the mode, and c is the high value. U [a, b]: uniform distribution; a is the low and b is the high limit.

Figure 2 shows the developed simulation model of the shaft construction. Table 3 lists the activities' names, descriptions, durations, and costs for the microtunneling simulation model. The segmental shaft construction starts with surveying the location of the shaft followed by excavation of the required depth and area for placing the cutting edge and building the shaft collar. Once the excavation is complete, the cutting edge is placed in position. Next, the collar supporting the jacking arms is built, and the jacking arms are placed. Meanwhile, the shaft sections are hauled to the shaft's location where they are lifted and placed using a crane. Once a ring is completed, the shaft is jacked into the ground, and soil is excavated at the bottom of the shaft. After placing and jacking all of the rings, the cutting edge is removed and the shaft is dewatered. Finally, the bottom of the shaft is prepared to host the Microtunnel Boring Machine (MTBM). Once the construction of the shafts is complete, the construction of the tunnel can commence.

Table 3. Durations and costs of microtunneling activities.

Activity Name	Activity	Duration (min)		Cost (USD/min)	
		6 m Shaft	8 m Shaft	6 m Shaft	8 m Shaft
Surveying	Surveying the location of shaft	U [120, 180]		U [0.99, 1.83]	
Exc Surf	Excavating the required depth for placing cutting edge	U [31, 57]	U [55, 103]	U [2.17, 4.03]	
Tr Unload RetA	Dump truck cycle	U [40, 80]		U [0.65, 1.21]	

Table 3. *Cont.*

Activity Name	Activity		Duration (min)		Cost (USD/min)	
			6 m Shaft	**8 m Shaft**	**6 m Shaft**	**8 m Shaft**
Place_CutEdg	Placing cutting edge		T [14, 25, 47]		U [39.70, 73.74]	U [52.93, 98.31]
Foundation Jack	Building the foundation for the jacking arms		U [58, 108]	U [76, 140]	U [28.76, 53.42]	
Jack_Placing	Placing the jacking arms on the foundation		U [480, 960]		U [4.26, 7.90]	
Sec to site	Bringing the sections to the site		U [20, 40]		U [0.32, 0.59]	
FB Truck Return	Truck return		U [20, 40]		U [0.32, 0.59]	
Atch lift crane	Attaching the sections to the crane and lifting		T [1.6, 1.7, 2.3]		The cost of this activity is included in the cost of placing the shaft sections.	
Placing_Section	Placing the sections		T [2.4, 3.3, 4.5]		U [39.70, 73.74]	U [52.93, 98.31]
Pushing_Section	Pushing the shaft sections into the ground	Fine sand	T [88, 159, 278]	T [117, 213, 375]	U [1.94, 3.60]	
		Sand and gravel	T [255, 356, 376]	T [344, 477, 500]		
		Clay	T [476, 535, 667]	T [643, 711, 865]		
Soil Removal	Soil removal	Fine sand	U [86, 160]	U [152, 282]	U [2.95, 5.45]	
		Sand and gravel	U [117, 217]	U [207, 385]	U [3.00, 5.58]	
		Clay	U [146, 270]	U [258, 480]	U [3.18, 5.91]	
Remove-Jack	Removing the jacking arms		T [14, 25, 47]		U [4.1, 7.61]	
Dewater Shaft	Dewatering the shaft		N [600, 120]		U [2.28, 4.24]	
Shaft Found	Building the foundation of the shaft		U [161, 299]	U [286, 530]	U [28.76, 53.42]	
MTBM_Setup	MTBM installation in the shaft		N [1440, 480]		USD 134,000	
Exc Ground	Pushing MTBM	Fine sand	T [72, 130, 227]	T [87, 157, 275]	U [21,813, 40,509]	U [29,084, 54,012]
		Sand and gravel	T [152, 217, 234]	T [197, 277, 296]	U [27,4630, 51,003]	U [36,618, 68,004]
		Clay	T [301, 355, 449]	T [386, 433, 548]	U [33,114, 61,498]	U [44,452, 81,997]
Sec to Shaft	Bringing sections to the shaft		U [20, 40]		U [0.32, 0.59]	
FB_Truck_Return	Truck return		U [20, 40]		U [0.32, 0.59]	
Atch Sec Crane	Attaching sections to the crane and lifting		T [1.6, 1.7, 2.3]		The cost of these activities is included in the cost of pushing the tunnel sections.	
Lower Sec Shaf	Placing the sections		T [2.4, 3.3, 4.5]			
Placing_Jack	Placing the jacking collar		T [4.4, 5.6, 6.7]			
Connect Cables	Connecting the cables		T [28.9, 36.2, 48.1]			
Jacking_Process	Pushing tunnel sections; cost is per section	Fine sand	T [72, 130, 227]	T [87, 157, 275]	U [21,813, 40,509]	U [29,084, 54,012]
		Sand and gravel	T [152, 217, 234]	T [197, 277, 296]	U [27,463, 51,003]	U [36,618, 68,004]
		Clay	T [301, 355, 449]	T [386, 433, 548]	U [33,114, 61,498]	U [44,452, 81,997]
Replace_Jack	Replacing the jacking collar		T [5.18, 6.38, 7.33]		The cost of these activities is included in the cost of pushing the tunnel sections.	
Disconnect cabl	Disconnecting the cables		T [16.41, 18.53, 20.97]			
Disassemb MTBM	Disassembling the MTBM in the receiving shaft		N [10,080, 1440]		USD 134,000	
Cleaning	Cleaning the tunnel		N [3600, 720]		U [2.97, 5.51]	
Sealing_Joints	Sealing the joints of the tunnel sections		U [551, 1024]	U [736, 1367]	U [1.25, 2.33]	
Uti_Support	Installation of the utility supports		U [8117, 15,074]		U [6.98, 12.96]	
Uti Network	Installation of the utility networks		U [10,200, 18,942]		U [37.72, 70.06]	
MUT Network	Installation of the MUT's own network		U [10,347, 19,216]		U [28.93, 53.73]	
Found Pavement	Construction of the foundation of the pavement		U [23, 42]	U [40, 57]	U [85.44, 158.68]	
Final Pavement	Final pavement of the street		U [125, 232]	U [222, 413]	U [236.07, 438.41]	

N [a, b]: normal distribution; a is the mean and b is the standard deviation. T [a, b, c]: triangular distribution; a is the low, b is the mode, and c is the high value. U [a, b]: uniform distribution; a is the low and b is the high limit.

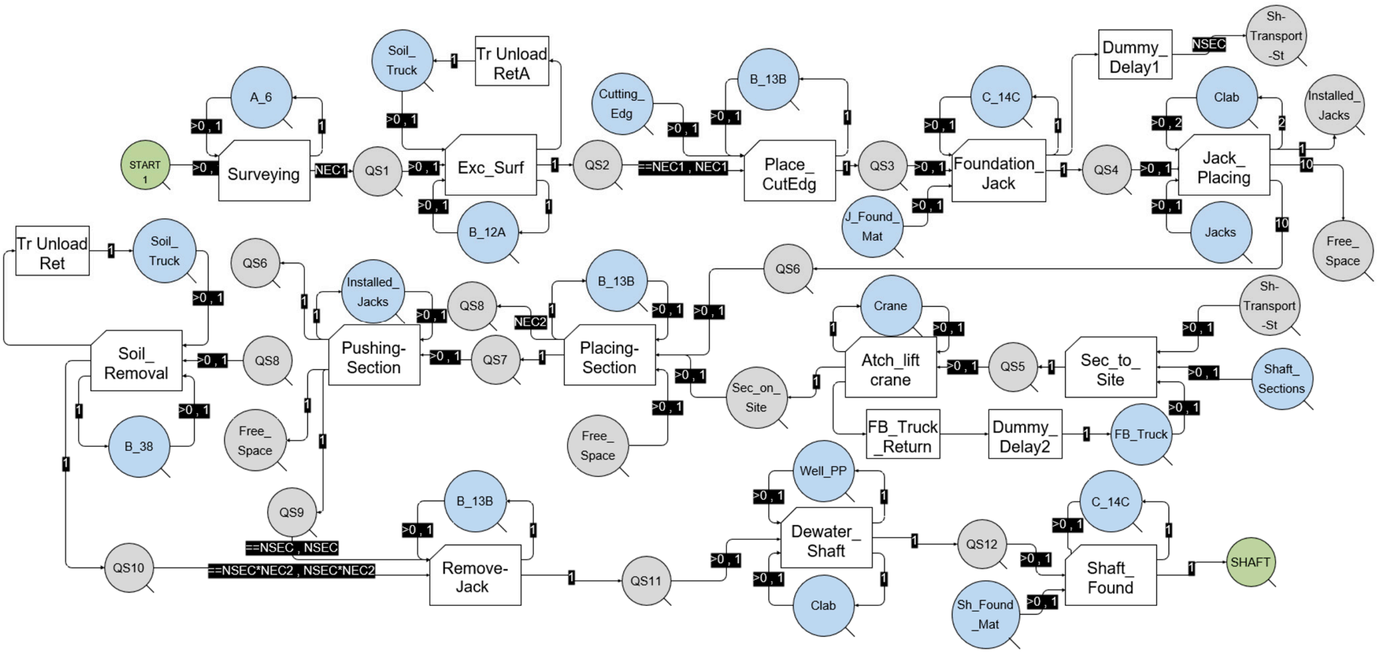


Figure 2. Shaft construction sequence using the segmental method.

Figure 3 shows the developed simulation model of the tunnel construction using microtunneling. The main activities of tunnel construction using microtunneling are (1) installing the MTBM in the starting shaft; (2) pushing the MTBM into the ground—once the MTBM is installed in the starting shaft, it will excavate the ground through the entrance ring so there will be a free space in the shaft to place the tunnel sections; (3) hauling the tunnel sections to the shaft; (4) attaching the sections to the crane and lifting them; (5) placing the sections; (6) placing the jacking collar behind the sections; (7) connecting the cables and pipelines; (8) pushing the sections into the ground; (9) replacing the jacking collar; (10) disconnecting the cables; (11) disassembling the MTBM when the tunnel is completely excavated; and (12) cleaning the tunnel. Once the shaft and the tunnel are constructed, the utilities can be installed in the tunnel.

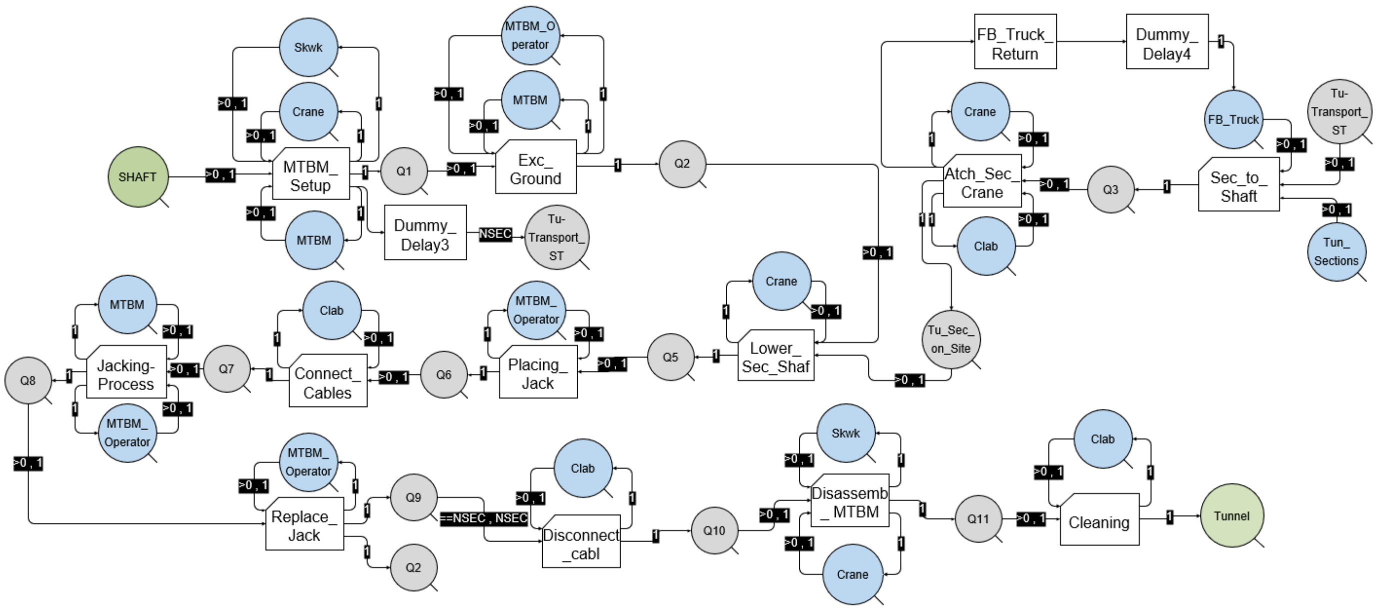


Figure 3. Tunnel construction sequence in microtunneling method.

Figure 4 shows the simulation model of placing the utilities in the tunnel. The first step is sealing the joints between the tunnel sections. Then, the required supports (e.g., hangers, trays) for the utilities are installed inside the tunnel. After installing the supports, the utility networks (e.g., cables, water pipes, gas pipes) can be installed. The MUT has its own networks, such as lighting systems, surveillance cameras, and fire detectors, which should be installed in the tunnel for security and safety. After placing the utilities in the tunnel, the surface of the street at the place of the starting and receiving shafts is repaired.

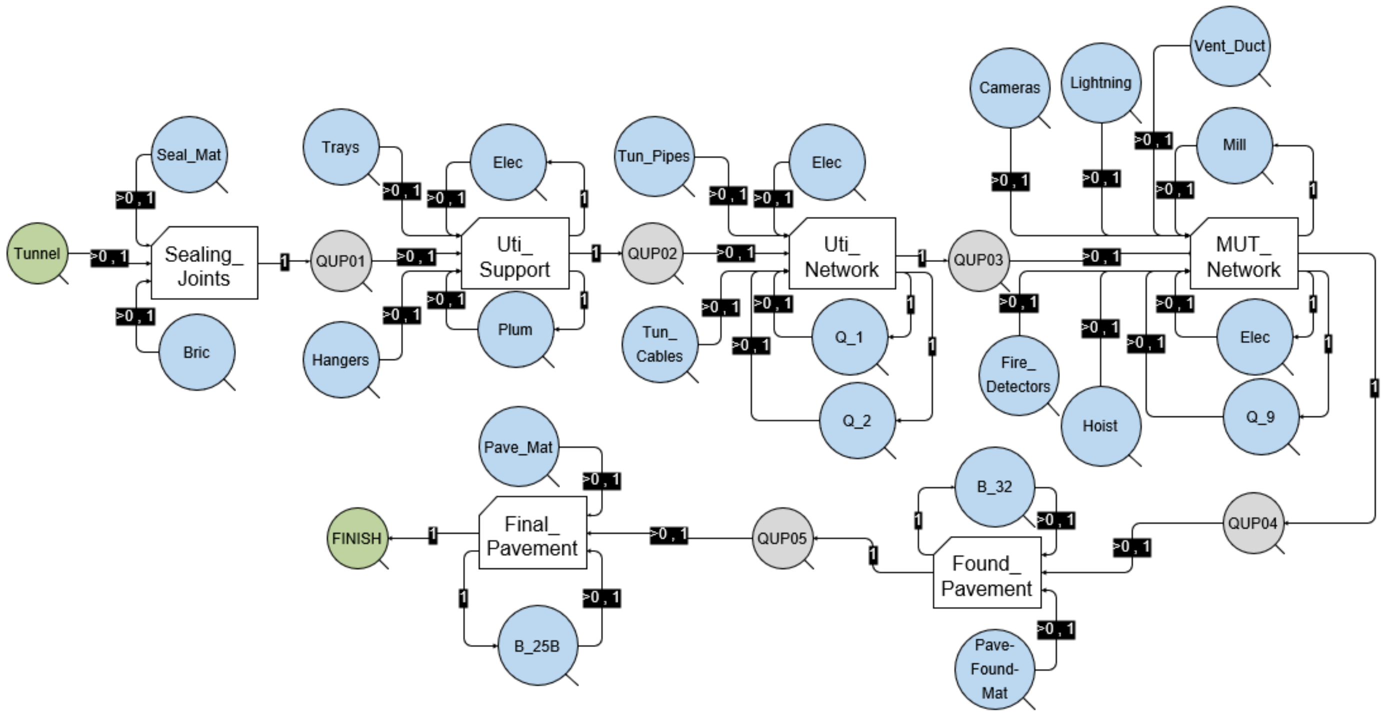


Figure 4. Construction sequence for placing utilities in the tunnel.

3. Results

3.1. Numerical Example Description

To demonstrate use of the proposed methodology, a numerical example of each construction method is presented. For this example, we chose downtown Montreal, Canada, as the tunnel location. Figure 5 shows the specifications of the electricity cables (red highlighted) and water pipes (blue highlighted), in the location of the project in GIS.

The diameter of the tunnel and the type of soil have a direct effect on the project duration and cost. Therefore, for each construction method, we evaluated six scenarios including two different tunnel diameters (i.e., 3 m or 4 m) and three different geotechnical conditions (i.e., fine sand, sand and gravel, or clay/marl) to analyze the construction time and cost of the MUT example. Table 4 lists the common variables of the MUT used to analyze both construction methods.

Table 4. Common variables of the MUT.

Attribute	Value
Tunnel length	100 m
Tunnel diameter	3 m or 4 m
Length of tunnel precast concrete sections	4 m
Depth of the tunnel	10 m
Working hours per day	8 h
Soil type	Fine sand, sand and gravel, or clay/marl

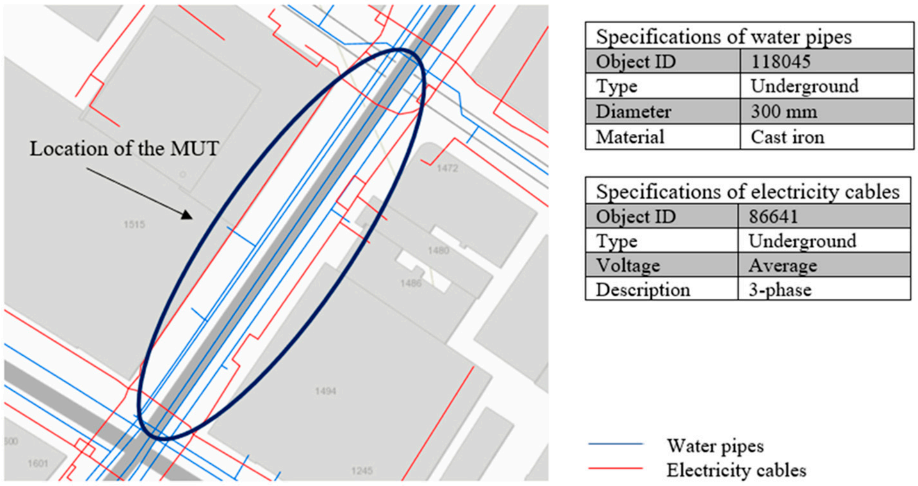


Figure 5. Specification of electricity cables and water pipes in the location of the MUT in ArcGIS.

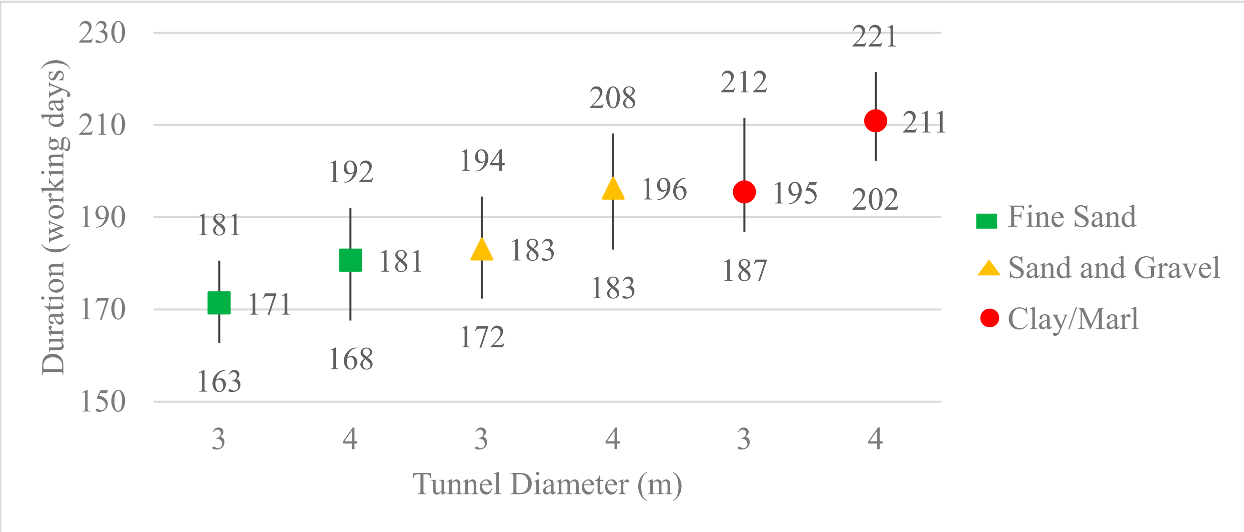
Under the C&C method, the entire length of the MUT is divided into equal segments built one by one. Each of these segments includes two 4 m precast concrete sections. For the microtunneling method, the diameter of the starting and receiving shafts is assumed to be 6 m and 8 m for the 3 m and 4 m tunnel diameters, respectively. Also, the depth of the shaft and the length of the shaft segments are assumed to be 10 m and 2 m, respectively. It should be noted that because of the difference between the assumed dimensions of the tunnel and those of the tunnels in reviewed projects, the pushing duration was modified according to the diameter and length of the sections.

3.2. Example Results

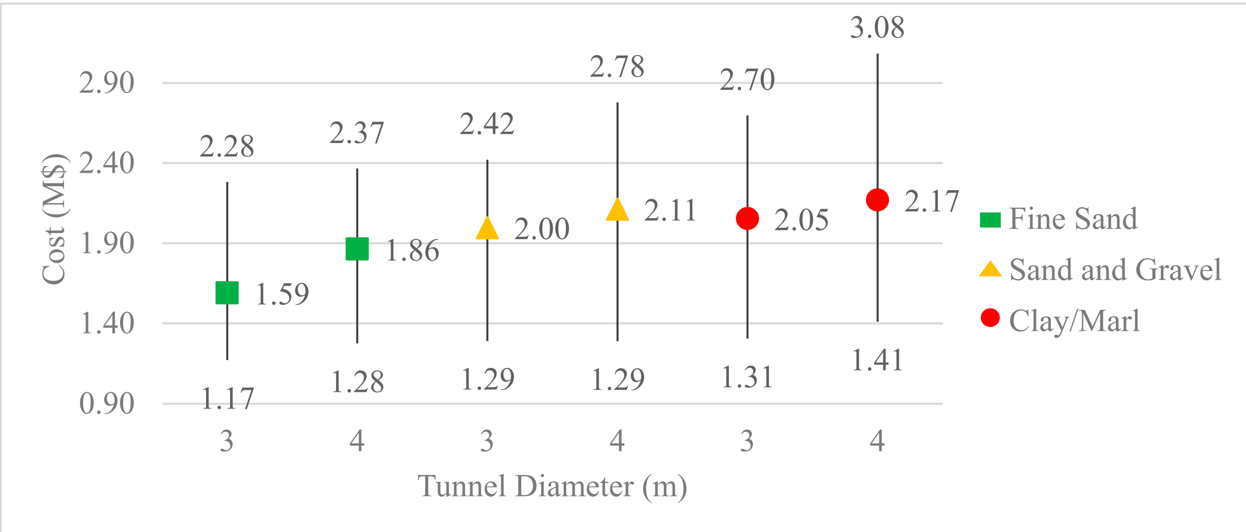
We verified and validated the simulation models by tracing the entities in the simulation model to ensure that the logic of the models was correct and they were running as expected. The numerical example data were fed into the developed simulation models. To capture the uncertainty in the activities' durations and costs, each model was run for 100 simulation replications. We calculated the total duration and cost of each MUT construction method by taking averages of the 100 replications.

Figure 6 shows the results of the C&C simulation for the two assumed diameters and three soil conditions. For the 3 m diameter tunnel, the estimated average total durations of MUT construction were 171, 183, and 195 working days and the total costs were USD 1.59 million, USD 2.00 million, and USD 2.05 million for the fine sand, sand and gravel, and clay/marl geotechnical conditions, respectively. For the 4 m diameter tunnel, the average total durations of tunnel construction were 181, 196, and 211 working days. The total costs were USD 1.86 million, USD 2.11 million, and USD 2.17 million for the fine sand, sand and gravel, and clay/marl geotechnical conditions, respectively. We also observed that by increasing the diameter of the tunnel or the hardness of the soil, the total duration and cost of the MUT increased.

Figure 7 shows the results of the microtunneling simulation for the two assumed diameters and three soil conditions. For the 3 m diameter tunnel, the estimated average total durations of MUT construction were 106, 108, and 122 working days and the total costs were USD 2.38 million, USD 2.76 million, and USD 3.02 million for the fine sand, sand and gravel, and clay/marl geotechnical conditions, respectively. For the 4 m diameter tunnel, the average total durations of MUT construction were 107, 117, and 129 working days. The total costs were USD 2.69 million, USD 2.97 million, and USD 3.41 million for the fine sand, sand and gravel, and clay/marl geotechnical conditions, respectively. We also found that by increasing the diameter of the tunnel or increasing the hardness of the soil, the total duration and cost of MUT construction increased as in the C&C example. These results indicate a time-cost tradeoff between the two construction methods. Microtunneling offers a shorter construction time but a higher cost when compared to C&C. Notably, taking the social cost into consideration could result in a comparable cost between the two construction methods.



(**a**)

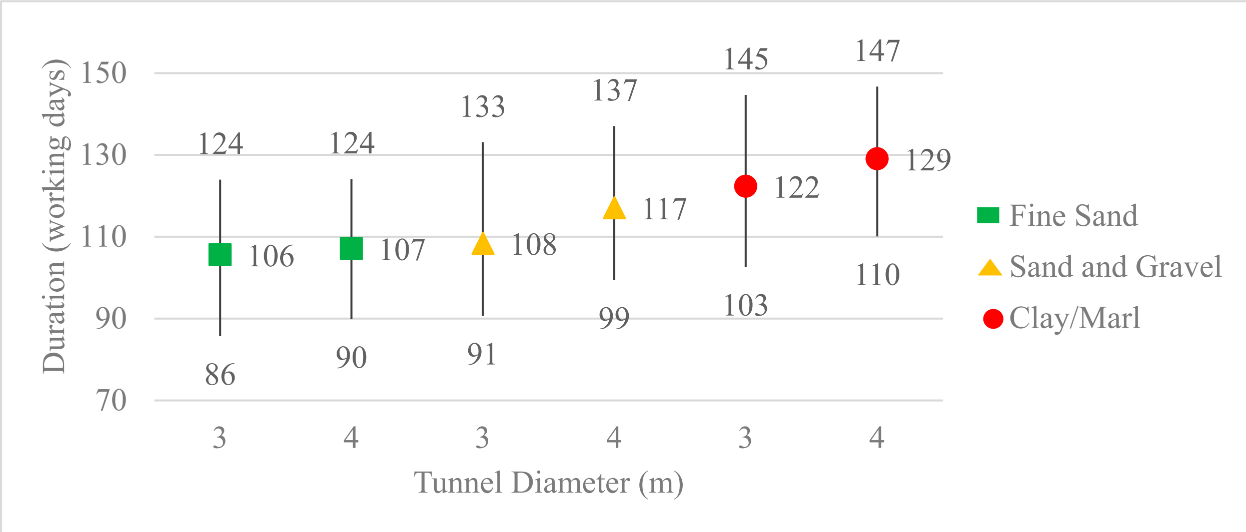


(**b**)

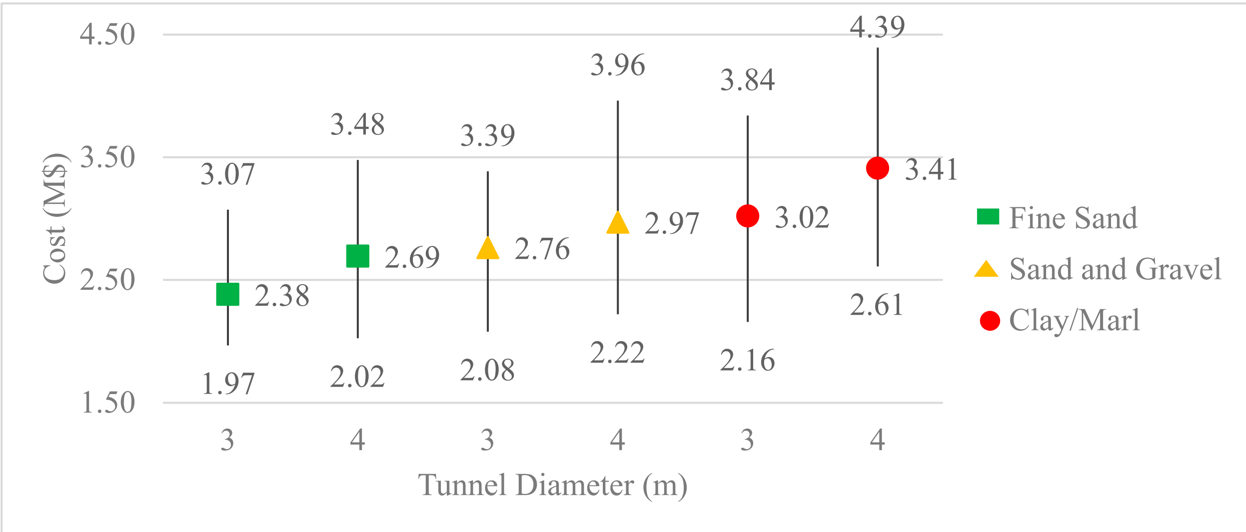
Figure 6. Results of DES of MUT construction using C&C: (**a**) durations of MUT construction vs. tunnel diameters in different geological conditions; and (**b**) costs of MUT construction vs. tunnel diameters in different geological conditions.

3.3. Four-Dimensional Modeling and Visualization

Existing modeling software, such as Autodesk Revit, does not have the MUT families built-in. As a result, we created new families to model the MUT. Next, we used Autodesk Infraworks Model Builder to add the 3D map of the area. Then, we imported the modeled MUT and the 3D map of the area into the Fuzor 2022 software and added the construction equipment and schedule of the project to create the 4D simulation of the construction methods. The 4D simulation can be used for constructability assessment of the MUT considering the spatio-temporal conflicts and impacts of the project on the surrounding area.



(**a**)

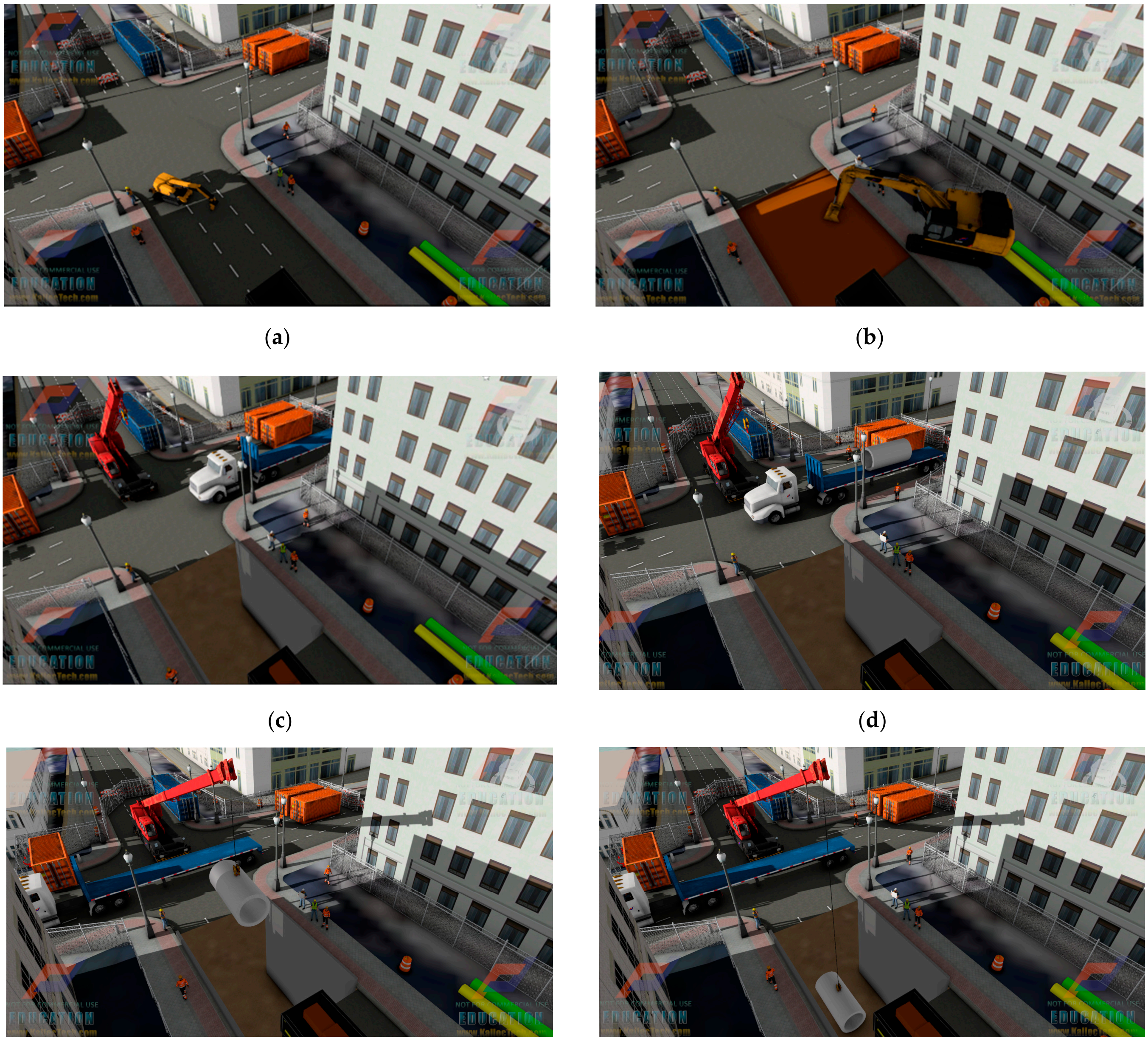


(**b**)

Figure 7. Results of DES of MUT construction using micortunneling: (**a**) durations of MUT construction vs. tunnel diameters in different geological conditions; and (**b**) costs of MUT construction vs. tunnel diameters in different geological conditions.

Figure 8 shows snapshots from the 4D simulation of MUT construction using the C&C method in Fuzor. In this figure, the pavement of the street is demolished (Figure 8a), the trench is excavated (Figure 8b), and the trench shoring system is installed (Figure 8c). Then the tunnel section is transported to the site (Figure 8d) and placed into the trench (Figure 8e).

Figure 9 shows snapshots from the 4D simulation of MUT construction using the microtunneling method in Fuzor. In this figure, the tunnel section is transported to the construction site by a truck (Figure 9a); the crane lifts it and moves it into the starting shaft (Figure 9b), where it is pushed into the ground using a jacking station (Figure 9c); and, at the same time, the MTBM is excavating the tunnel face. Figure 10 shows an underground view of the MUT in Fuzor. As shown in this figure, since the MUT is built under the current utilities, removing or diverting the old utilities is not necessary.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 8. Four-dimensional simulation of MUT construction using C&C in Fuzor 2022 software: (**a**) demolition of the pavement; (**b**) trench excavation; (**c**) installation of trench shoring system; (**d**) delivering a section to the site; and (**e**,**f**) lowering the tunnel section.

The 4D simulation can be used for constructability assessment (e.g., to consider the spatio-conflicts and impacts of the construction on the surrounding areas) and verification that there are no errors in modeling the construction process. In addition, experts, field personnel and decision-makers can discover differences between the way they understand the operation and the way the model developer understands it (validation). As an example of potential spatio-temporal conflicts, if there was a mechanical problem of the microtunneling boring machine that took 450 min to repair, then the duration of finishing the activity of pushing the next tunnel section would extend from the average value of 150 min to 600 min because of the mechanical problem. Consequently, not only would the whole project be delayed, but also the new tunnel sections transported near the shaft should be stacked on the site, assuming that it was not possible to postpone the delivery of the sections to the site. Because the average time to transport one section to the site is 30 min, 15 sections would arrive during this delay. Figure 11 shows an example of this situation, which may create a spatio-temporal conflict with the crane movement.

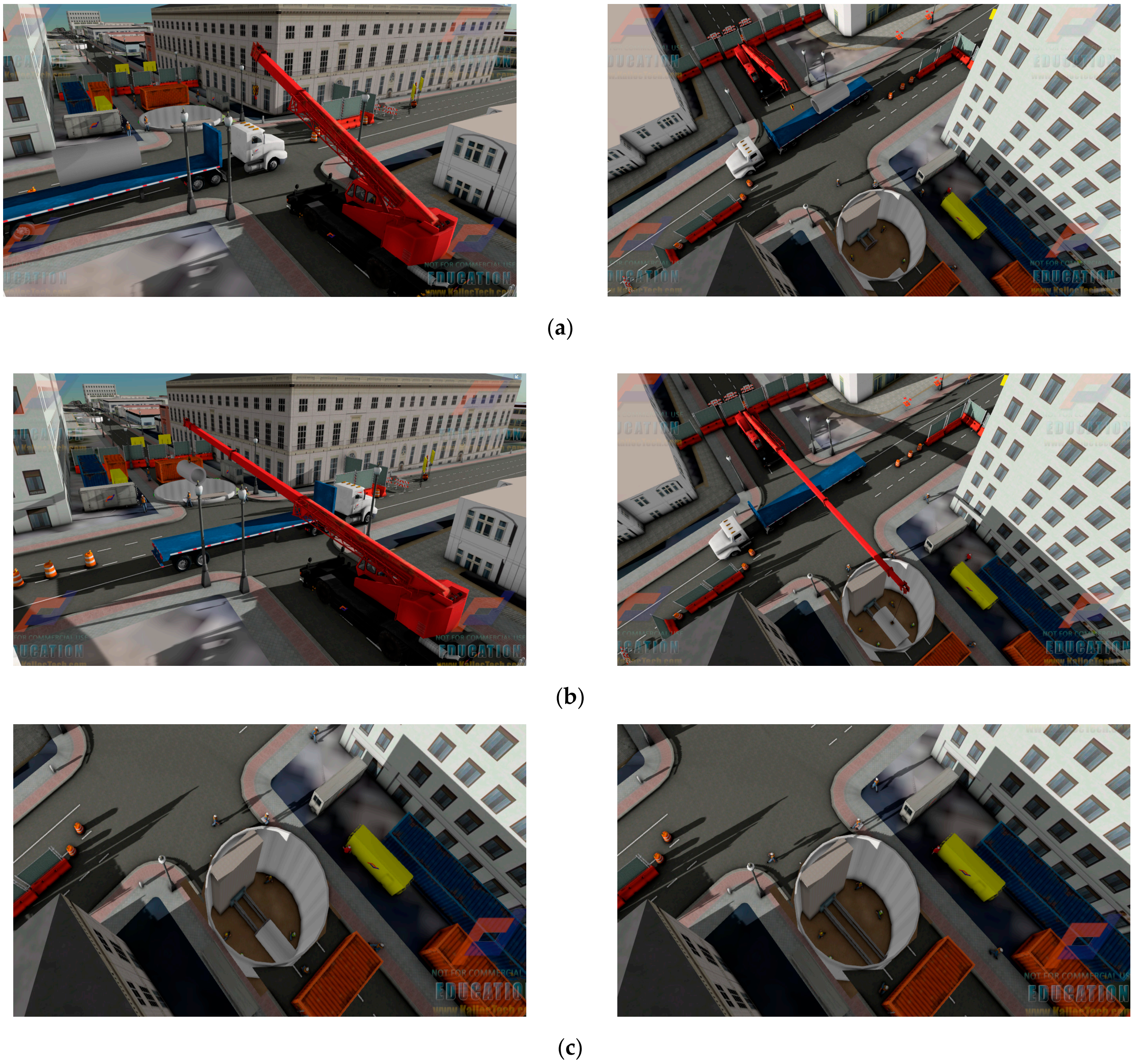


Figure 9. Four-dimensional simulation of MUT construction using microtunneling in Fuzor 2022 software: (**a**) delivering tunnel section to the construction site; (**b**) lifting and placing the section into the starting shaft; and (**c**) pushing the section into the ground.

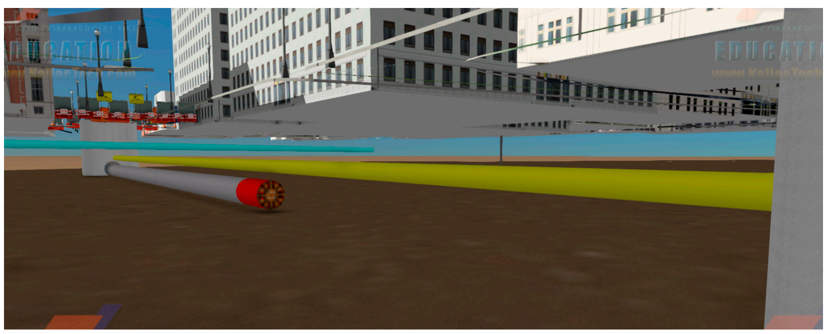


Figure 10. Underground view of the MUT in Fuzor.

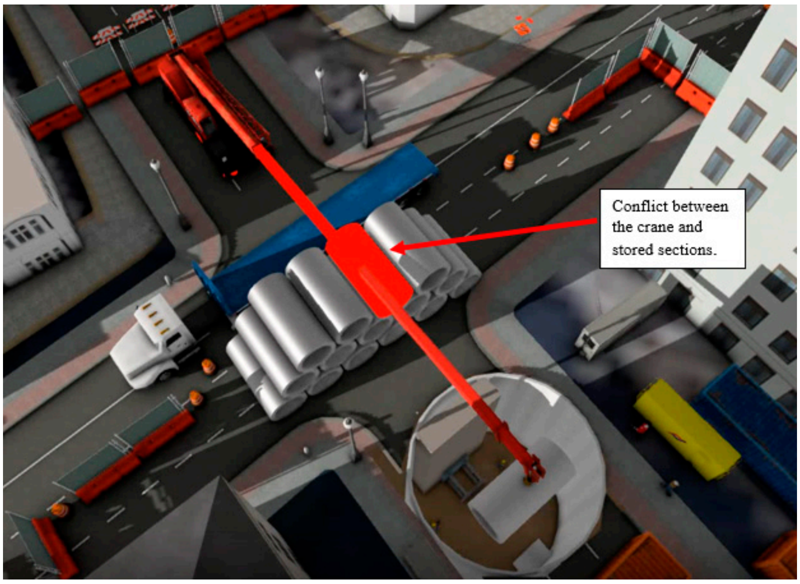


Figure 11. Example of a situation that can cause spatio-temporal conflict.

4. Discussion

Two construction methods, microtunneling and C&C, for constructing an MUT were compared. Based on the simulation results for different tunnel diameters and soil conditions, the main findings are (1) in the microtunneling method, by increasing the diameter of the tunnel from 3 m to 4 m, the total duration of the project increased by 2%, 7%, and 5% and the total cost of the project increased by 10%, 11%, and 16% in fine sand, sand and gravel, and clay/marl soil conditions, respectively; (2) in the C&C method, by increasing the diameter of the tunnel from 3 m to 4 m, the total duration of the project increased by 5%, 7%, and 7% and the total cost of the project increased by 10%, 7%, and 9% in fine sand, sand and gravel, and clay/marl geotechnical conditions, respectively; (3) the duration of MUT construction using C&C is more sensitive than microtunneling to changes in tunnel diameter; (4) the cost of MUT construction using microtunneling is more sensitive than C&C to changes in tunnel diameter; (5) on average, microtunneling is 52% more expensive and 66% faster than the C&C method; and (6) the impact of the microtunneling method on the surrounding area and old utilities is less than the C&C method.

5. Conclusions

This paper applied the stochastic simulation approach to model MUT construction. The developed models can be used to calculate the total duration and cost of the MUT construction project. The 4D simulation can be used for constructability assessment of the MUT project considering the spatio-temporal conflicts and impacts of the MUT on the surrounding area.

Despite the advantages of the proposed method, it has the following limitations, which will be addressed in future work: (1) the social cost of the MUT construction is an important factor that was not considered in this study. As an example, the city of Montreal had a plan for building an MUT under Sainte-Catherine Street because it would reduce the social cost during the operation phase [45]. However, they only considered the C&C construction method, which would result in a high social cost during the construction phase. Therefore, the project was canceled. Future work will compare the costs of MUT construction methods, including social costs, by considering different factors, such as the period of time that the road is closed because of construction. (2) In this paper, the proposed method was performed for a short MUT of 100 m in length. Therefore, by increasing the length of the tunnel, the microtunneling method can become a more competitive alternative to C&C because the setup cost is a fixed cost. Future work will apply the proposed method for different lengths of MUT. (3) In this paper, only the main tunnel was considered. Future work should consider connecting the utilities from the MUT to the surrounding buildings and the construction of the transversal tunnels. (4) The current DES models do not include special events such as the malfunctioning of equipment, and they do not take into consideration the risk of change in the type of soil during the MUT construction. Future work will include modeling the risk of equipment breakdown and geotechnical variation. (5) The 4D simulation is developed manually. Future work should automate the process of developing a stochastic 4D simulation of MUT construction methods.

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References

1. Alaghbandrad, A.; Hammad, A. Framework for multi-purpose utility tunnel lifecycle cost assessment and cost-sharing. *Tunn. Undergr. Space Technol.* **2020**, *104*, 103528. [CrossRef]
2. Ormsby, C.M. *A Framework for Estimating the Total Cost of Buried Municipal Infrastructure Renewal Projects*; McGill University: Montreal, QC, Canada, 2009.
3. Gagnon, M.; Gaudreault, V.; Overton, D. *Age of Public Infrastructure: A Provincial Perspective*; Statistics: Ottawa, ON, Canada, 2008.
4. Oum, N. *Modeling Socio-Economic Impacts of Infrastructure Works*; Concordia University: Montreal, QC, Canada, 2017.
5. Apak, M.Y.; Ozen, H.; Calis, M.; Golgeli, B.; Ataoglu, S. Applications of utility tunnels for natural gas pipelines. *Tunn. Undergr. Space Technol.* **2022**, *122*, 104243. [CrossRef]
6. Cao, Y.; Gong, Z.; Li, N.; Wang, Q. How to Guarantee the Sustainable Operation and Maintenance of Urban Utility Tunnels? From the Perspective of Stakeholder and the Whole Life Cycle. *Buildings* **2023**, *13*, 1810. [CrossRef]
7. Canto-Perello, J.; Curiel-Esparza, J. Assessing governance issues of urban utility tunnels. *Tunn. Undergr. Space Technol.* **2013**, *33*, 82–87. [CrossRef]
8. Curiel-Esparza, J.; Canto-Perello, J.; Calvo, M.A. Establishing sustainable strategies in urban underground engineering. *Sci. Eng. Ethics* **2004**, *10*, 523–530. [CrossRef] [PubMed]
9. Wu, C.; Wu, P.; Jiang, R.; Wang, J.; Wang, X.; Wan, M. Evaluating the economic and social benefits of multiutility tunnels with an agent-based simulation approach. *Eng. Constr. Archit. Manag.* **2022**, *29*, 1–25. [CrossRef]
10. Sun, F.; Liu, C. An Exploratory Pledging Framework of Crowdfunding for Utilities Tunnel Engineering Project. *Math. Probl. Eng.* **2022**, *2022*, 4658454. [CrossRef]
11. He, H. Incentive Mechanism of Utility Tunnel PPP Projects with User Involvement. *Sustainability* **2023**, *15*, 10771. [CrossRef]
12. Genger, K.T.; Hammad, A.; Oum, N. Multi-objective optimization for selecting potential locations of multi-purpose utility tunnels considering agency and social lifecycle costs. *Tunn. Undergr. Space Technol.* **2023**, *140*, 105305. [CrossRef]
13. Thomas, H.R.; Maloney, W.F.; Horner, R.M.W.; Smith, G.R.; Handa, V.K.; Sanders, S.R. Modeling construction labor productivity. *J. Constr. Eng. Manag.* **1990**, *116*, 705–726. [CrossRef]
14. de Sol, C. *Guide Pratique des Galeries Multiréseaux*; Techni. Cités: Verrières le Buisson, France, 2005.
15. Ramírez Chasco, F.D.A.; Meneses, A.S.; Cobo, E.P. Lezkairu Utilities Tunnel. *Pract. Period. Struct. Des. Constr.* **2011**, *16*, 73–81. [CrossRef]
16. Byron, A.; Baker, J.; Condif, E.; Cotterell, J. *MTC Utility Tunnel Design Final Report*; Brigham Young University: Provo, UT, USA, 2015.
17. Shannon, R.E. Simulation modeling and methodology. *ACM SIGSIM Simul. Dig.* **1977**, *8*, 33–38. [CrossRef]
18. AbouRizk, S.M.; Halpin, D.W.; Lutz, J.D. State of the art in construction simulation. In Proceedings of the 24th Conference on Winter Simulation, Arlington, VA, USA, 13–16 December 1992; pp. 1271–1277. [CrossRef]
19. Mawlana, M.; Vahdatikhaki, F.; Doriani, A.; Hammad, A. Integrating 4D modeling and discrete event simulation for phasing evaluation of elevated urban highway reconstruction projects. *Autom. Constr.* **2015**, *60*, 25–38. [CrossRef]
20. Al-Bataineh, M.; AbouRizk, S.; Parkis, H. Using simulation to plan tunnel construction. *J. Constr. Eng. Manag.* **2013**, *139*, 564–571. [CrossRef]
21. Liu, D.; Zhou, Y.; Jiao, K. TBM construction process simulation and performance optimization. *Trans. Tianjin Univ.* **2010**, *16*, 194–202. [CrossRef]
22. Rahm, T.; Scheffer, M.; Thewes, M.; König, M.; Duhme, R. Evaluation of disturbances in mechanized tunneling using process simulation. *Comput.-Aided Civ. Infrastruct. Eng.* **2016**, *31*, 176–192. [CrossRef]

23. Ruwanpura, J.Y.; AbouRizk, S.M.; Er, K.; Fernando, S. Special purpose simulation templates for tunnel construction operations. *Can. J. Civ. Eng.* **2001**, *28*, 222–237. [CrossRef]
24. Touran, A.; Asai, T. Simulation of tunneling operations. *J. Constr. Eng. Manag.* **1987**, *113*, 554–568. [CrossRef]
25. Abdallah, M.; Marzouk, M. Planning of tunneling projects using computer simulation and fuzzy decision making. *J. Civ. Eng. Manag.* **2013**, *19*, 591–607. [CrossRef]
26. Dang, T.T.; Schoesser, B.; Thewes, M.; Koenig, M. Evaluation of productivities influenced by disturbances and different soil compositions in microtunnelling using process simulation. *Tunn. Undergr. Space Technol.* **2018**, *76*, 10–20. [CrossRef]
27. Luo, R.Y.; Najafi, M. Productivity study of microtunneling pipe installation using simulation. *J. Infrastruct. Syst.* **2007**, *13*, 247–260. [CrossRef]
28. Marzouk, M.; Abdallah, M.; El-Said, M. Modeling microtunneling projects using computer simulation. *J. Constr. Eng. Manag.* **2010**, *136*, 670–682. [CrossRef]
29. Moharrami, S.; Taghaddos, M.; RazaviAlavi, S.; AbouRizk, S. A hybrid simulation approach for microtunneling construction planning. *Constr. Innov.* **2021**, *21*, 363–378. [CrossRef]
30. Nido, A.A.; Knies, C.J.; Abraham, D.M. Role of operation simulation in the analysis and improvement of microtunnelling projects. *Tunn. Undergr. Space Technol.* **1999**, *14*, 1–19. [CrossRef]
31. Jorjam, S.; Hammad, A. Discrete Event Simulation of Multi-purpose Utility Tunnels Construction Using Microtunneling. In Proceedings of the International Symposium on Automation and Robotics in Construction, Dubai, United Arab Emirates, 2–4 November 2021; IAARC Publications: Dubai, United Arab Emirates, 2021; pp. 303–310.
32. Koo, B.; Fischer, M. Feasibility study of 4D CAD in commercial construction. *J. Constr. Eng. Manag.* **2000**, *126*, 251–260. [CrossRef]
33. Hartmann, T.; Gao, J.; Fischer, M. Areas of application for 3D and 4D models on construction projects. *J. Constr. Eng. Manag.* **2008**, *134*, 776–785. [CrossRef]
34. Genger, T.K.; Luo, Y.; Hammad, A. Multi-criteria spatial analysis for location selection of multi-purpose utility tunnels. *Tunn. Undergr. Space Technol.* **2021**, *115*, 104073. [CrossRef]
35. Allen, T.T. *Introduction to Discrete Event Simulation and Agent-Based Modeling: Voting Systems, Health Care, Military, and Manufacturing*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2011. [CrossRef]
36. Martinez, J.C. EZStrobe-general-purpose simulation system based on activity cycle diagrams. In Proceedings of the 2001 Winter Simulation Conference (Cat. No. 01CH37304), Arlington, VA, USA, 9–12 December 2001; IEEE: New York, NY, USA, 2001; pp. 1556–1564. [CrossRef]
37. Gil-Martín, L.M.; Hernández-Montes, E.; Shin, M.; Aschheim, M. Developments in excavation bracing systems. *Tunn. Undergr. Space Technol.* **2012**, *31*, 107–116. [CrossRef]
38. Marzouk, M.; Abdallah, M.; El-Said, M. Modeling Cut and Cover Tunnels Using Computer Simulation. In Proceedings of the 5th International Engineering and Construction Conference, Los Angeles, CA, USA, 27–29 August 2008; ASCE: Reston, VA, USA; p. 717.
39. Najafi, M.; Gokhale, S.B. *Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal*; McGraw-Hill Education: New York, NY, USA, 2005.
40. Stein, D. *Trenchless Technology for Installation of Cables and Pipelines*; Stein & Partner: Bochum, Germany, 2005.
41. Technology, F.S.F.T. *Microtunneling and Horizontal Drilling: Recommendations*; ISTE Ltd.: Newport Beach, CA, USA, 2006. [CrossRef]
42. Valdenebro, J.-V.; Gimena, F.N.; López, J.J. Construction process for the implementation of urban utility tunnels in historic centres. *Tunn. Undergr. Space Technol.* **2019**, *89*, 38–49. [CrossRef]
43. Dang, T.T. Analysis of Microtunnelling Using Process Simulation Module. In *ISRM VietRock International Workshop*; ISRM: Hanoi, Vietnam, 2015; p. ISRM–VIETROCK–2015-047.
44. Doheny, M. *Building Construction Costs with RSMeans Data*; Gordian RSMeans Data: Rockland, MA, USA, 2021.
45. Gagnon, M. Une première galerie multiréseaux en sol québécois. In *Portail Constructo*; Médias Transcontinental S.E.N.C.: Montreal, QC, Canada, 2020.