Modeling the Effect of Subjective Factors on Productivity of Trenchless Technology Application to Buried Infrastructure Systems

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Abstract: Trenchless technology (TT) includes a large family of methods utilized for installing and rehabilitating underground utility systems with minimal surface disruption and destruction resulting from conventional excavation. Productivity of TT techniques is affected by a number of subjective factors that need to be evaluated. A productivity index (PI) model is developed in order to represent this subjective effect in refining productivity assessment. The analytic hierarchy process and fuzzy logic are used to develop the proposed PI model that relies on the actual performance of 12 subfactors under three main categories: management, environmental, and physical conditions. The developed PI model resulted in PI equal to 0.7323 and 0.7251 for microtunneling and horizontal directional drilling (HDD) projects, respectively. Multiattribute decision support system software is developed to determine the PI for a specific TT technique using Visual Basic. The PI model is tested, which shows reasonable results. This research is relevant to both industry practitioners and researchers. It provides practitioners with a model that justifies their productivity calculation by quantifying subjective factors effect, which will affect their schedule and cost estimation for trenchless projects. In addition, it provides researchers with the development methodology for the PI model.

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Introduction

One of the largest problems facing Canada and the United States today is the rehabilitation of its decaying underground infrastructure (utility systems). These infrastructure systems include: (1) water and wastewater distribution systems; (2) gas, petroleum, and chemical pipelines; (3) electrical and communications networks; (4) access ways; and (5) other small diameter tunnels utilized in variety of applications. Although Canadian municipalities spent \$12–15 billions annually on these infrastructure systems, they are decaying at a faster rate than they are being renewed (NRC 2002). According to a 1997 study by the Canadian Water and Wastewater Association (CWWA), the need for new and upgraded water and sewer infrastructure in Canada was estimated to be \$88.4 billion over the period 1997–2012: municipal water and sewer systems needed \$28.0 and \$60.4 billion, respectively (\$5.9 billion annually) (Siddiqui and Mirza 1996; Vander Ploeg 2003). Experts have evaluated Canadian water and sewer infrastructure as inadequate and in need of substantial investment (Infrastructure Canada 2004). Therefore, Canadian municipalities face a great challenge of managing this large work volume of replacement and new construction projects efficiently. Since many of these existing utility systems are located in congested or urban areas, the installation and rehabilitation methods using open-cut (OC) construction cause significant service disruption; parking lots, streets, and driveways destruction; traffic disruption; and unsafe trenches to pedestrians (Chung et al. 2004; Lueke and Ariaratnam 2001). With increased urbanization, undesirable noise, sight pollution, and surface congestion have increased, making it more costly, if not impossible in some situations, to employ the OC method. For these reasons, it becomes apparent that trenchless technology (TT) is necessary to alleviate some of the OC shortcomings (Lueke and Ariaratnam 2001).

TT describes the installation, renovation, replacement, or rehabilitation of conduits beneath ground surface and roadways without continuous, open-cut excavation between them (Hegab and Salem 2004). The term has been used on a global basis since the mid-1980s; however, some of these methods are not new. For example, auger boring and slurry boring have been used since the early 1940s, and pipe jacking has been used since the early 20th century (Allouche and Ariaratnam 2002; Cheung et al. 2000). According to the North America Society of Trenchless Technology (NASTT), trenchless construction is defined as "a family of methods, materials, and equipment used for construction, replacement, or rehabilitation of existing underground infrastructure with minimal disruption to traffic, businesses, and other activities" (Chung et al. 2004; Allouche et al. 2000). Using TT reduces the cost of utility projects. Several studies have compared TT to OC, which shows that the initial cost of OC is lower than TT and the

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social cost (SC) associated with the OC is much more than that of TT (Gangavarapu 2003; and Gangavarapu et al. 2003).

With the increased usage of TT techniques in underground construction and rehabilitation, factors that affect their productivity have to be investigated. Most factors are subjective in nature, which complicate the productivity assessment process. Based on literature and experts, this study categorized these factors under three major categories: management, environmental, and physical conditions as shown in Table 1 (Myers et al. 1999; Salem et al. 2003). Management conditions include managerial skills, safety regulations, equipment mechanical conditions, and operator skills. On the other hand, environmental conditions include soil and site conditions, unseen soil obstacles, as well as water table level. Pipe characteristics, such as type, length, usage, and depth, constitute the third category of physical conditions. The aforementioned factors' effect on productivity has to be quantified in order to facilitate the TT estimator's job.

Estimating productivity of TT methods can be divided into two main steps: (1) assess the effect of subjective factors on productivity and (2) calculate productivity considering the quantitative factors, such as activities duration, quantities, equipment and labor rates, etc. The first step is studied in this paper. Because of the factors' subjectivity, the analytic hierarchy process (AHP) and fuzzy logic (FL) are potential techniques to quantify their effect on productivity. The second step will be done in future research where the TT method will be added as a major factor because all activities' duration depend on the utilized TT method. Typically, productivity of TT methods is predicted using heuristic techniques and expert opinions (common practice) without considering the effect of subjective factors. In addition, there is a lack of models that predict productivity of TT methods considering the effect of subjective factors.

Therefore, the main objective of this research is to develop a PI model that quantifies the effect of subjective factors on productivity of TT methods using the integrated AHP/FL techniques. In addition, an automated tool is developed to demonstrate the PI methodology and assess the value of PI for specific TT projects. Consequently, determining productivity is outside this paper's scope because it only predicts the subjective factors effect on productivity. Productivity calculation will be included in future research.

Background of AHP Methodology

The AHP, which was developed by Saaty, is a decision model that uses pairwise comparison matrices to evaluate alternatives with respect to quantitative and qualitative factors (Saaty 1980). It can be used in individual or group decision settings taking into account the experience and intuition of the decision maker. The AHP methodology is used, in current research, in order to quantify the effect of subjective factors on productivity of TT methods. The AHP application algorithm can be summarized as follows (Zayed and Chang 2002; Zayed and Halpin 2004):

1. Identify qualitative factors that need to be evaluated;
2. Construct a pairwise comparison matrix among these factors. It is a reciprocal matrix where the value of the main diagonal elements is one and the values below the main diagonal are reciprocal to those that are above;
3. Calculate the consistency index (CI) to check the pairwise matrix consistency, using Eq. (1) as follows:

$$CI = (\lambda_{max} - m)/(m-1) \tag{1}$$

   where m=size of the matrix; and λ_{max}=maximum eigenvalue of this matrix;
4. Calculate the consistency ratio (CR)=CI/random index (RI), where the RI is given by Saaty (1980). The CR has to be <0.1; otherwise, the matrix will be considered inconsistent;
5. If the matrix is inconsistent, it will be returned to the experts to adjust and re-evaluate their estimation and repeat steps 2–4; and
6. If it is consistent, then accept the weight vector that is generated from the matrix by the AHP method. This vector represents the relative weights of the factors that are included in the matrix.

Subjective Factor Effect Model

The subjective factor effect (SFE) model is designed to assess the effect of subjective factors on the productivity of TT techniques. It provides a logical and reliable consistent method to assess the productivity index (PI) based on 12 factors within three main categories as shown in Table 1. Ideal productivity can be

Table 1. Productivity Factors for Trenchless Technology Techniques

	Factors	Description
Management conditions	Managerial skills	It covers management of resources and site activities
	Operator's efficiency	It covers operators experience, characteristic, and personality
	Safety regulations	It covers regulations that may impact the TT operations on site
	Mechanical condition	Maintenance/repair as well as the status of TT equipment
Environmental conditions	Unseen soil obstacles	Unseen underground soil problems, such as old foundation, other utilities, existing foundation, etc.
	Water table level	Existence of ground water level impact job operations and affect the penetration conditions
	Soil condition	Production rate differs from one soil type to another based on its toughness
	Site condition	It covers site nature, equipment, and staff moving availability
Physical conditions	Pipe size	Diameter of the installed pipe will affect productivity
	Pipe length	Impact of pipe's length characteristic on productivity
	Pipe usage	It covers the usage of pipe (sewer, water, or gas)
	Pipe depth	Depth of operation will affect productivity of the machine

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determined considering productive time of 60 min/h neglecting the effect of subjective factors. The PI value will be multiplied by the ideal productivity in order to consider the effect of these subjective factors. The PI value can be assessed using the SFE value, which can be determined using the following Eq. (2) based on Zayed and Halpin (2004)

$$\mathrm{SFE} = \sum_{i=1}^{i=n} W_i^* E_i(x_i) \tag{2}$$

where W_i=decomposed weight of factor i; $E_i(x_i)$=effect value for factor i; and n=number of factors.

The SFE model uses 12 productivity factors (n=12) where the overall contribution of each factor is given by its effect value $E_i(x_i)$ multiplied by its decomposed weight W_i. The term (x_i) is added to the model in order to allow inclusion of any extended future work using subfactors. The effect value of a factor $E_i(x_i)$ reflects the value of its performance level as it exists for a specific project. A subjective performance scale (1–9) is used to determine the $E_i(x_i)$ for each productivity factor. The decomposed relative weight of a factor W_i reflects its relative importance to the other factors. The factor's relative weights (W_i) are obtained using the aforementioned AHP algorithm.

The principal difference between W_i and $E_i(x_i)$ is that a factor might be important in the process but it does not affect the productivity of a specific project. Therefore, W_i represents the global importance of a factor in the process as a whole. The $E_i(x_i)$ represents the effect of these factors on specified projects because they might cause problems in the TT process regardless of their importance in the process. A factor that is less important with small weight may cause a large impact on productivity and vice versa. For example, unseen soil obstacles have a considerably low decomposed weight; however, it has a large effect on sample projects.

Productivity Index

The PI represents the proportion of productive time achieved when utilizing a specific TT technique on a given project. Its inverse is the SFE, which represents the effect of these factors on productivity of a specific TT technique in a particular infrastructure project. The PI is the reverse of nonproductive time (total time−nonproductive time). However, the SFE represents the nonproductive time. Then, the relationship between PI and SFE can be explained as shown in the following Eq. (3)

$$\mathrm{PI} = 1 - \mathrm{SFE} \tag{3}$$

Research Methodology

Fig. 1 shows the various steps that this research passes through to arrive at conclusions. Productivity factors are identified and collected from TT projects and experts through a pilot survey. Accordingly, a questionnaire is designed to collect the required information to generate the PI value for specified TT techniques. Data are collected from consultants, contractors, and equipment operators who are specialists in the TT techniques. Based on the collected data, the W_i and $E_i(x_i)$ values are calculated using the AHP and FL, respectively. Both terms will be calculated for each productivity factor. The summation of their multiplication will generate the SFE value for the TT technique. The PI value is determined using the aforementioned Eq. (3). Based on the above steps, an automated tool, using Visual Basic, is generated to calculate the PI value. It will be described later in this paper. Finally, the model developed is tested to show its reliability in determining the PI value.

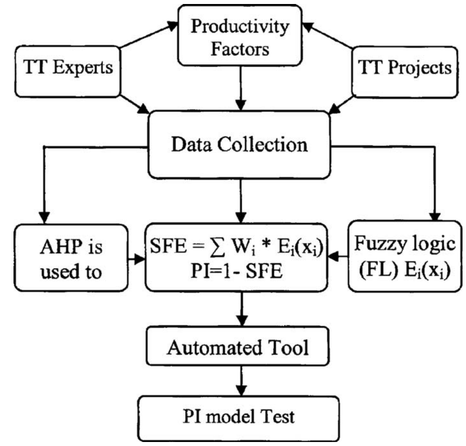

Fig. 1. Study methodology flowchart

Data Collection

A pilot survey is designed based on the literature and the authors experience to investigate the most effective factors on the TT method's productivity. The pilot survey is sent to experts in the trenchless technology field asking them to select the most influential factors on the TT methods' productivity giving them the opportunity to add or delete factors. Based on the results of the pilot survey, a questionnaire is designed. The questionnaire is used to collect data from consultants, contractors, and equipment operators who are specialists in the TT methods. The questionnaire is divided into four different parts. The first and second parts are designed to collect the participant's and project's information. The third part is designed to collect the effect of various factors on productivity using a unified fuzzy performance scale. This step is used to build the effect value $E_i(x_i)$. The participants are given the opportunity to add more factors and evaluate their impact. The last part collects pairwise comparison matrices by comparing the factors against each other in order to develop the W_i using the AHP algorithm. Approximately 50 questionnaires are sent to the experts in United States and Canada; however, only 20% are received [ten replies (projects)]. All replies only represent new construction in clay and sand soils. Six of these projects are constructed using microtunneling; however, the other four are constructed using horizontal directional drilling (HDD). Twenty percent of these data (two projects: one microtunneling and one HDD) are used for testing purposes. Based on the questionnaires received, this study determines the average PI value for microtunneling and HDD techniques.

PI Model Application

W_i Determination

The weight (W_i) of each factor in the TT process is calculated using the aforementioned AHP algorithm. The CI and CR=CI/RI of each matrix are determined to check their consistency. If CR<0.1 then the matrix is consistent; otherwise,

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it would have to return to the participant to adjust and re-evaluate his/her assessment. Results show that all collected matrices are consistent with CR < 0.1.

Each matrix generates a weight vector for each main and subfactors. Therefore, the decomposed weight concept is used to generate the global weight of each submain factor. For example, if the weight of the soil condition subfactor is 0.37 and the environment as a main category is 0.312, then the decomposed weight of the soil conditions is 0.312*0.37=0.1155 as shown in Table 2. Similarly, the decomposed weight for each factor is determined. Table 2 shows that "safety regulations" is the highest factor that affects productivity of TT projects because their decomposed weight is 0.2090. The second highest factor is the equipment operator, whereas his/her skills greatly affect productivity (decomposed weight is 0.1452). Managerial skills and soil conditions also considerably affect productivity with decomposed weights of 0.1298 and 0.1155, respectively. Other factors are within the average range of 5%.

$E_i(x_i)$ Determination

The rating of $E_i(x_i)$ is performed based on the performance scale (1–9) shown in Fig. 2. This rating will be determined for each productivity factor in a specific project. Hence, the company or contractor will be able to determine the PI index based on Eqs. (1) and (2) for such projects. However, if a company or a contractor (e.g., HDD contractor) would like to calculate a global $E_i(x_i)$ value for its projects so that it will be used for preplanning purposes and calculating the contractor's efficiency, he/she will be able to do so by averaging his/her $E_i(x_i)$ values for previous projects. Due to the paper size limitation, only average values of $E_i(x_i)$ for the collected information on microtunneling and HDD projects are presented as shown in Table 2. It shows, for microtunneling projects, that unseen soil obstacles, pipe ground depth, and site conditions are the most sensitive factors to productivity with an average value of 0.4 (slightly ineffective to productivity) out of 0.9 in the performance scale. On the other hand, managerial skills, safety regulations, water table, and pipeline usage have an average value of 0.3 (moderately ineffective to productivity) out of 0.9 in the performance scale. Other factors have values of, on average, 0.2 (substantially ineffective) out of 0.9. These values of three or two out of nine show that these factors have a minimal effect on the productivity of TT methods. In the HDD projects, managerial skills, soil conditions, and site conditions are the most sensitive factors to productivity with an average $E_i(x_i)$ value of 0.4.

PI Value

The SFE value can be determined based upon the values of W_i and $E_i(x_i)$ as shown in Table 2. The model in Eq. (2) is applied to calculate the SFE value. Table 2 shows that the SFE value is 0.2677 and 0.2749 for microtunneling and HDD projects, respectively. Eq. (3) is used to calculate the PI value, which is 0.7323 and 0.7251 for microtunneling and HDD projects, respectively. This value shows that, on average, microtunneling and HDD projects are working with 73.23 and 72.51% efficiency due to subjective productivity factors, respectively. To raise this efficiency, preventive actions have to be assured in order to reduce the effect of high impact factors to productivity. For example, the SFE value for safety regulations is the highest among other factors (0.0627) in microtunneling projects and one of the highest (0.0418) in HDD projects, which raises a flag on these regulations. The management of TT projects has to seek possible solutions for the influence of these regulations in order to increase productivity. On the other hand, managerial skills come in as the second priority (0.0389) and the highest (0.0519) for microtunneling and HDD projects, respectively, which can easily be enhanced by changing the ways of resource allocation and site activities so that productivity is not affected. Table 2 diagnoses the various factors that cause troubles in the site; therefore, it is essential for practitioners to build similar tables for their projects and take preventive actions against trouble spots.

Automated Tool Development and Coding

Based upon the methodology of this research, an automated tool is developed to determine the PI of any TT technique. It is standalone software that uses Visual Basic application on the EXCEL spreadsheet environment. Fig. 3 shows the layout of this auto-

Table 2. Subjective Factor Effect and Productivity Index Determination

i	Qualitative factors	W_i (avg.)	Average $E_i(x_i)$		$W_i^* E_i(x_i)$	
			Microtunneling	HDD	Microtunneling	HDD
1	Managerial Skills	0.1298	0.3	0.4	0.0389	0.0519
2	Machine operator	0.1452	0.2	0.3	0.0290	0.0436
3	Safety regulations	0.2090	0.3	0.2	0.0627	0.0418
4	Mechanical condition	0.0561	0.2	0.3	0.0112	0.0168
5	Unseen soil obstacles	0.0610	0.4	0.2	0.0244	0.0122
6	Ground water table	0.0591	0.3	0.2	0.0177	0.0118
7	Soil condition	0.1155	0.2	0.4	0.0231	0.0462
8	Site condition	0.0644	0.4	0.4	0.0258	0.0258
9	Pipe type	0.0432	0.1	0.1	0.0043	0.0043
10	Pipe length	0.0320	0.2	0.3	0.0064	0.0096
11	Pipe usage	0.0575	0.3	0.1	0.0173	0.0058
12	Pipe ground depth	0.0172	0.4	0.3	0.0069	0.0052
		SFE=$\Sigma[W_i^* E_i(x_i)]$	—	—	0.2677	0.2749
		PI=1-SFE	—	—	0.7323	0.7251

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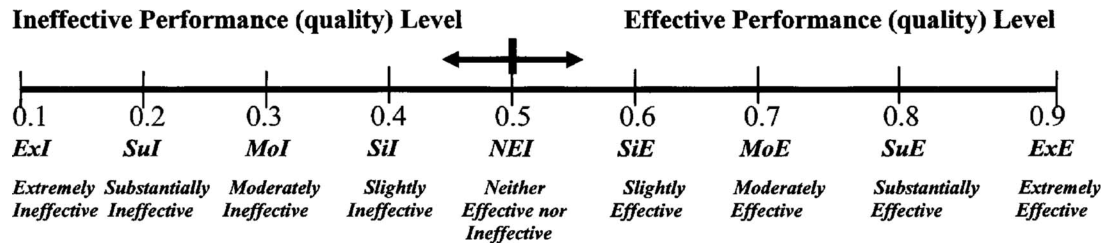

Fig. 2. Subjective performance scale for productivity factors

mated tool. After entering the required data, the program calls various modules to determine the PI value. These modules include λ_{max}, CI, CR, W_i, and $E_i(x_i)$ modules. Each module determines the value of its parameter. For example, the CR module calculates the value of CR and compares it to 0.1. If it is <0.1 then it accepts the matrix as consistent and proceeds to calculate the W_i and $E_i(x_i)$ values. If not, it goes back to the data entry environment to fix the matrix before using its weight vector in the calculation. If the matrix is consistent, the value of SFE and PI will be calculated based on the value of W_i and $E_i(x_i)$ for each factor and reports are generated to show these values. A detailed description of this layout is shown in the following sections.

Data Entry

The pairwise comparison matrices for different factors are entered into the automated tool (software) in addition to the evaluation of each factor using a performance scale (1–9). The program is designed to accept up to 10×10 matrices, which accommodates matrices that compare ten factors to each other. The user is asked to fill out the size, name of each factor, and the pairwise comparison relationships among these various factors. Fig. 4 shows a pair-wise comparison matrix of a 3×3 size (data entry screen). Once the relative importance for each factor is entered into the software, it starts calling the appropriate modules to check the matrix consistency.

Data Processing

After calling various modules to check matrix consistency, the CR value is calculated. If it is >0.1, then the software generates a remark mentioning that the matrix is inconsistent and redirects the user to the data entry screen to re-enter the matrix after fixing its problems or to enter a new matrix. If it is consistent, the software calls the other modules and completes the analysis. The sample analysis screen in Fig. 4 shows the matrix and the values of λ_{max}, CI, and CR. It also shows whether this matrix is consistent or not in addition to the weight vector (W_i) for this matrix, which is used to calculate the PI value. It also has an option to go back to the data entry screen to enter new matrices and complete the PI calculation. Other screens are not included in this paper due to size limitations.

The developed tool assists TT contractors in controlling their current projects and managing future projects. It shows the potential factors that generate troubles in current projects or those that might generate troubles in future projects. Therefore, the developed tool can work as preplanning and controlling tools for future and current projects, respectively. Remedial and preventive actions can be taken to reduce the effect of these potential factors based on the developed tool's assessment.

Model Test

Results of the designed model and the developed automated tool are compared to the results of the test data set [20% of the collected data (two projects: one microtunneling and one HDD)] to check their reliability in assessing the PI value. The efficiency of each reply is collected from the questionnaire sent to reviewers. They are asked to provide information (i.e., efficiency, etc.) for an average project. The collected actual efficiency of microtunneling

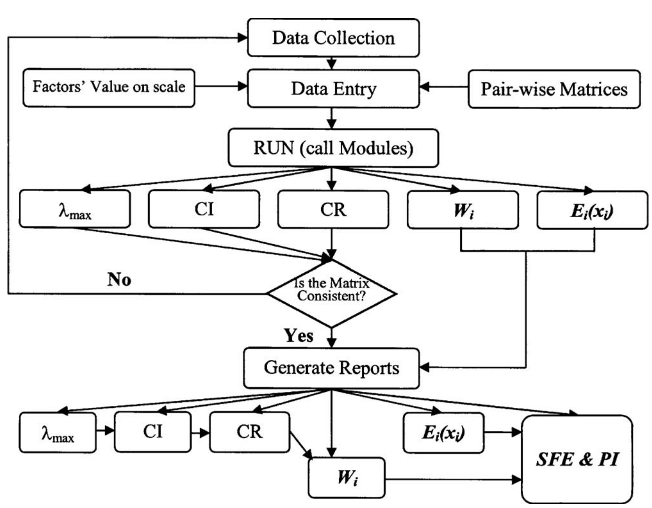

Fig. 3. Proposed layout for PI automated tool

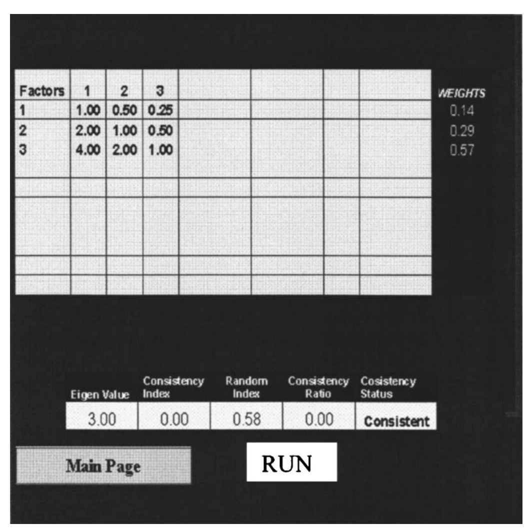

Fig. 4. Analysis screen

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and HDD projects are 0.77 and 0.83, respectively. However, the PI value, based on the models developed, is 0.7323 and 0.7251 for microtunneling and HDD projects, respectively. Therefore, the percents reliability for the model developed for microtunneling and HDD projects are 95.10 and 87.36%, respectively. These reliability percents are reasonable and acceptable to test the model developed. It is recommended to increase the test data set in order to validate the results of the model developed.

Conclusions

A methodology of calculating the PI for TT techniques is developed using the AHP and FL in order to assist contractors and consultants in scheduling and bidding their projects with higher efficiency and accuracy. A model is developed to assess the PI value for TT techniques. An automated tool (software) is designed based on the model developed. It is a decision support tool, which is designed using Visual Basic programming on an EXCEL spreadsheet environment. The designed tool is tested where its reliability in assessing the PI value for microtunneling and HDD projects are 95.10 and 87.36%, respectively. This early result inspires confidence in the robustness of the methodology and the designed model. The model developed is limited to microtunneling and HDD projects, which are used for only new construction in clay and sand soils. Therefore, it is recommended to increase the data set, TT methods, and their usage for rehabilitation as well as new construction.

This research is relevant to both industry practitioners and researchers. It provides practitioners with a model that justifies their productivity calculation by quantifying subjective factor effects. This will affect their schedule and cost estimation for trenchless projects. In addition, it provides researchers with the factors that contribute to productivity of TT methods, the development methodology for the PI model, and the automated tool that can be used in similar research applications.

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