PREDICTING TUNNEL BORING MACHINE UTILIZATION USING DISCRETE EVENT SIMULATION MODELS FOR HARD ROCKS

by

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A thesis submitted to the Faculty and the Board of Trustee of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Underground construction and tunneling).

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ABSTRACT

Tunnel Boring Machines (TBM) are perhaps the most efficient method for tunnel excavation, as they have become the dominant mode and method of tunneling around the world. One of the essential steps for justification of the use of TBMs as well as planning the completion time and estimating the cost of projects involving TBMs is estimating the machine performance in given ground conditions. The main performance indicator for TBMs is the average daily advance rate (AR) which is product of rate of penetration (ROP), utilization (U). While there are various models for estimation of machine ROP with acceptable levels of accuracy and reliability, the models for prediction of machine utilization are often not sufficiently accurate and do not include many of the critical input information. This is because the predictive models for estimation of machine utilization do not have the capability to deal with many of the site-specific issues, including variation in geological settings, TBM and backup specifications, and site set up and logistics. Improving the accuracy of models for TBM performance prediction by estimation of utilization has been the focus of many ongoing studies in mechanized tunneling. It requires accounting for many factors including project geology, machine design and configuration, and operational issues. Simulation of tunnel activities considering TBM to be a tunneling factory can be a reliable method for estimation of TBM utilization factor. In this study, modeling tunneling activities and downtimes using discrete event simulation approach is adopted to predict TBM utilization. A few mechanized tunneling projects in hard rock have been considered for development of the model and verification of the results. A database template using visual basic for application (VBA) and data from available projects is established where the project and machine specifications along with the various geotechnical unit details serve as the input parameter for the simulation. The simulation model, CSM2020 is prepared using Arena© simulation

software. The results of modeling were verified by comparing the estimated utilization with that of the recorded TBM utilization at the jobsites, broken down by formations and reaches of tunnel. This allowed for verification of the capabilities of the modeling concept to incorporate the impacts of geology and tunnel length. Sensitivity analysis of the model relative to certain activities allows for evaluating the ability of the simulation system to account for each activity and its impact on machine performance within a given geology and at certain reach of the tunnel.

Parametric studies were conducted relative to various input parameters to the simulation model including geology, machine specification, and site set up to see the response of the model to various input parameters and to assess their impact on the utilization. The results were compared to some case histories for verification and proved that the modeling concept is functional. To apply the DES model to different projects, data recording, screening, and analysis protocols have been developed to allow for adjustment of the models with additional onsite input data. This approach was tried by both Arena© and the MATLAB code and site data for 8 different projects.

The impact of interdependencies of various tunneling activities on machine utilization were also assessed to identify the critical activities that might act as bottlenecks in the excavation process. In parallel, a code was developed in MATLAB to allow for performing DES modeling with better control of the process and data structure for individual activities and resources. The code also has the advantage that it does not require Arena© license to run and can be made into an executable program. In general, use of CSM2020 DES model for utilization estimation prove to be a promising approach which can be further developed to include additional features and be expanded to variety of tunneling operation, while it can be further developed to be used as part of a system for optimization of tunneling operation and selection of TBMs with a quantitative approach to evaluate various features of the machine and backup system.

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Dedication

This thesis is dedicated to

My priceless daughter, Ilina

My loving husband, Sandeep

My beloved sister, Anshu

And my parents.

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CHAPTER 1

INTRODUCTION

1.1 Background

The increasing demand for underground space as part of civil infrastructure to support urbanization in recent decades has resulted in a significant technological development in its construction related methodology. The demand for tunneling and underground space is expected to increase in foreseeable future with the growing need to have longer and deeper tunnels to serve various aspects of modern living.

Tunnel Boring Machines (TBMs) have gained huge acceptance in the tunneling industry for excavating tunnels due to their efficiency and safety, wide area application in variable geology and site conditions, and speed of tunneling. They also offer many advantages over conventional drill and blast methods such as reduced construction time and improved overall tunnel stability (Singh and Zoldy, 2012). The use of TBMs in any project involves huge investment and risk related to operating the machine in the given ground condition and their overall performance. Therefore, attempt should be made to use these machines to their full potential to justify the capital investment and to reduce the cost of tunneling projects. As pointed out by Rostami (2016) and Laughton (1998), maximum utilization for TBMs is around 50%, while the typical utilization is in the range of 20-30%. This means that for only 50%, or most likely around 25% of the total shift/daytime, the machine is working and excavating the ground, and the rest of shift time (~75%) is spent in support activities. Hence, there is a need to identify the bottlenecks in the performance of TBMs. Further, the accuracy of TBM performance prediction models are not very good in integrating the complexity of a job site in the TBM operation into the performance estimates. This refers to accuracy of the available models for prediction of Rate of Penetration (ROP), which are mostly in

the acceptable +/- 15%, and the models for prediction of machine utilization which is in +/-20% range.

Machine utilization (U) is a factor that is defined as the percent of time when machine is excavating out of the total project time. It is one of the key parameters linking advance rate (AR) and rate of penetration (ROP) using the following formula:

$$AR\ (m/day) = ROP(m/h) \times 24\ (h/day) \times U/100 \qquad \text{Equation 1}$$

Here, AR it is the length of tunnel excavated per day and ROP is the rate at the which the TBMs penetrate the ground. Machine utilization depends on the type of operation (e.g. tunnel size, grade, curves, etc.), management, maintenance of machine, surveying and capacity /setting of the backup system. Lower utilization reflects excavating curves and slopes, mismatch between the machine and backup system or their shortcomings, operating in adverse ground conditions, poor management and/or frequent machine break down. On the other hand, high utilization is achieved for relatively straight tunnels with slight up slope in favorable ground conditions coupled with proper machine specification and matching backup system, good management and maintenance practices (Rostami and Ozdemir, 1993).

There are various components of a project site that affects the overall performance of the machine and they are shown in Figure 1.1. It comprises of TBM cutterhead, back-up system, transportation system for muck and supplies, site set up, portal and shafts. Installation of California switches allows for trains to pass and therefore the delay due to transportation can be reduced. The easy access of supplies from the portal location to the TBM face reduces the delays caused due to unavailable supplies at the face. The details of the back-up area are shown in Figure 1.2. It illustrates the various components involved in the TBM operation at the back up. Hence,

estimation of TBM utilization (U) should encompass all these parameters in addition to ground related factors like support installations, probe-drilling and pre-excavation grouting.

In order to estimate TBM Utilization factor, following questions need to be addressed:

1. Which tunneling activities are affecting the Utilization factor?
2. To what extent these activities cause delay in operation and hence reduce machine Utilization?
3. What are the input parameters required for the estimation of Utilization factor?
4. How is the interaction between the different tunneling activities and their stochastic nature considered in the model?
5. Are the activities sensitive to geological setting and site set up?
6. What are the time distributions of these activities and how do they change with TBM size, backup, and operator's experience?

There are several TBM performance prediction models that have been introduced over the years. The list of existing performance prediction models is given in chronological order in Table 1.1.

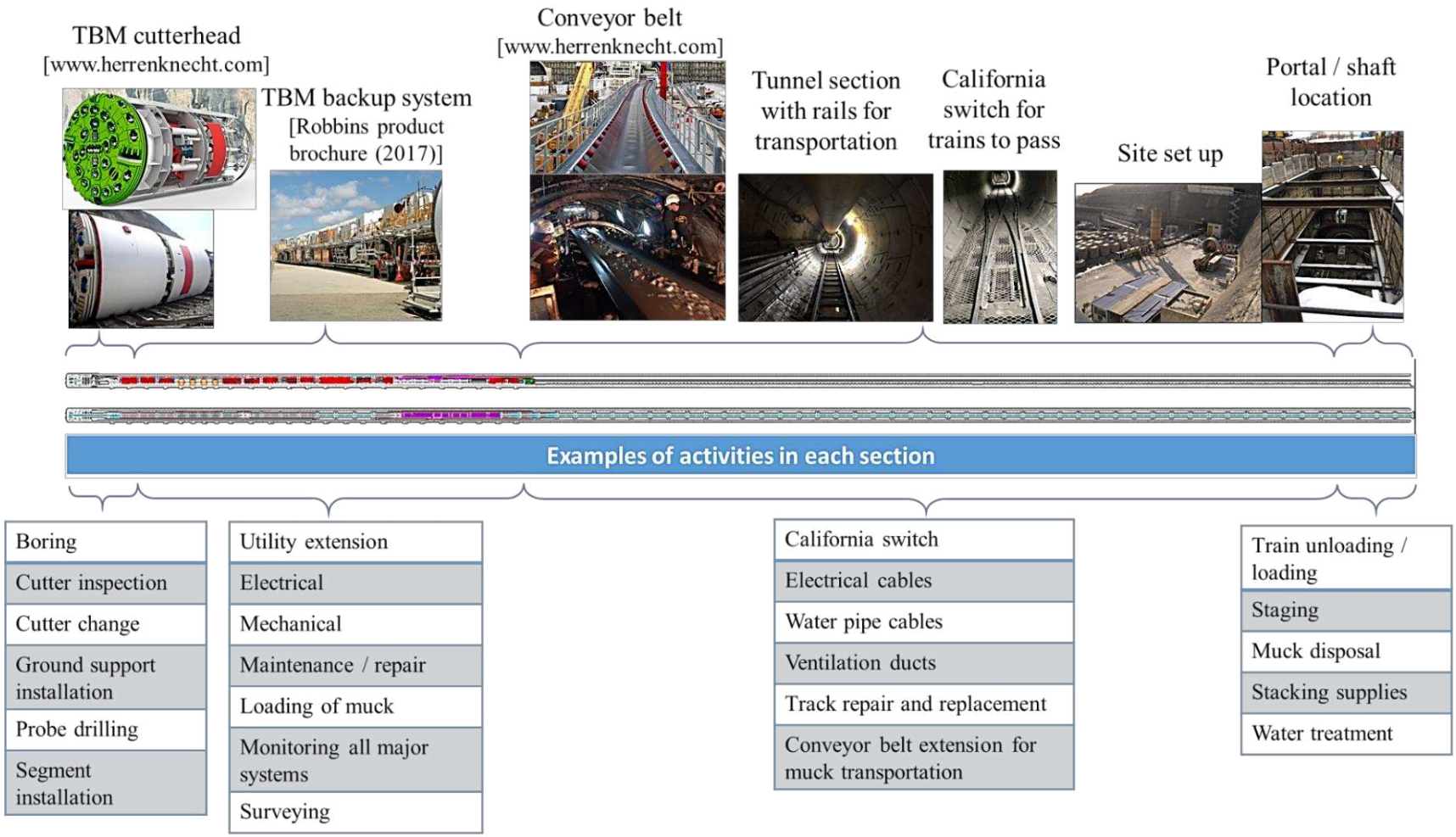
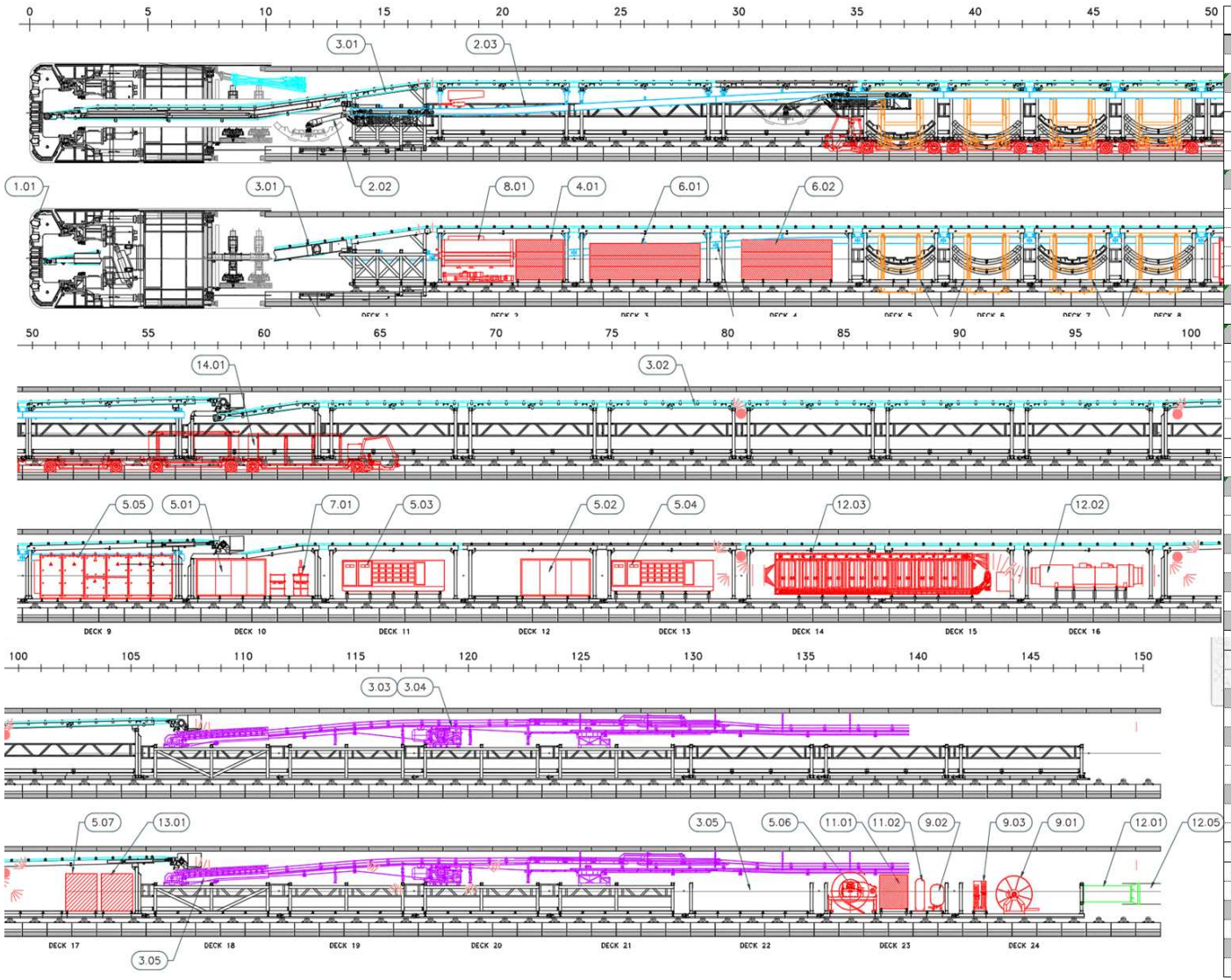


Figure 1.1 Schematic diagram showing components of TBM and project site



ITEM	DESCRIPTION
1.00	TBM
1.01	TBM
2.00	SEGMENT HANDLING
2.01	SEGMENT FEEDER
2.02	SEGMENT HANDLING CRANE
2.03	SEGMENT HANDLING CRANE RUNWAY
2.04	SEGMENT UNLOADER
3.00	DEMUCKING SYSTEM
3.01	BELT CONVEYOR 1
3.02	BELT CONVEYOR 2
3.03	TUNNEL CONTINUOUS CONVEYOR
3.04	TUNNEL CONTINUOUS CONVEYOR ELECTRIC PANEL
3.05	CONVEYOR STRUCTURES STORAGE AREA
4.00	GUIDANCE SYSTEM
4.01	CONTROL CABIN
5.00	ELECTRICAL SYSTEM
5.01	TBM ELECTRICAL PANEL
5.02	BUP ELECTRICAL PANEL
5.03	M.V TRANSFORMER No.1
5.04	M.V TRANSFORMER No.2
5.05	VFD ELECTRIC PANEL
5.06	M.V CABLE REEL
5.07	TBM EMERGENCY DIESEL GENERATOR
6.00	HYDRAULIC SYSTEM
6.01	HYDRAULIC POWER PACK No.1
6.02	HYDRAULIC POWER PACK No.2
7.00	GREASING SYSTEM
7.01	GREASE PUMPS
8.00	GROUT INJECTION SYSTEM
8.01	GROUTING SYSTEM
9.00	INDUSTRIAL WATER SYSTEM
9.01	HOSE REEL FOR INCOMING INDUSTRIAL WATER
9.02	PRESSURIZED WATER TANK
9.03	INCOMING INDUSTRIAL WATER PUMPS
10.00	DEWATERING SYSTEM
10.01	DEWATERING PUMPS FROM SHIELD
11.00	COMPRESSED AIR SYSTEM
11.01	INDUSTRIAL AIR COMPRESSOR
11.02	AIR TANK
12.00	VENTILATION SYSTEM
12.01	VENTILATION DUCT STORAGE CASSETTE
12.02	DUST AIR FAN AND SYLENCER
12.03	DEDUSTER
12.04	DUST AIR DUCT LINE
12.05	TUNNEL VENTILATION DUCT
13.00	SPECIAL REQUIREMNTS
13.01	FIRST AID EQUIPMENT BOX
14.00	TRAIN
14.01	SERVICE TRAIN

Figure 1.2 Schematic diagram TBM cutterhead and backup area (SELI)

Table 1.1 Summary of TBM performance prediction models in the literature

References/Models	Output
Roxborough and Phillips (1975)	ROP
Graham (1976)	ROP (mm/rev)
Ozdemir, CSM(1977)	ROP
Farmer et al. (1980)	ROP (mm/rev)
Snowdon et al. (1982)	ROP
Nelson et al. (1983)	ROP
Sanio (1985)	ROP
Hughes (1986)	ROP for coal mines
Sato et al. (1991)	ROP
Innaurato et al. (1991)	ROP (m/h) based on RSR
Rostami and Ozdemir, CSM (1993)	ROP, U and AR
O'Rourke et al. (1994)	ROP. Based on total hardness and field penetration index
Palmstrom (1995), RMi	ROP
Bruland (1998), NTNU	ROP, U and AR
Barton (2000), Q_{TBM}	ROP, U and AR
Grima et al. (2000)	AR
Yagiz (2002), MCSM	ROP
Bernados and Kaliampakos (2004)	AR
Bieniawski (2007), RME	AR
Yagiz (2008)	ROP based on field data
Gong and Zhao (2009)	ROP based on field data
Hassanpour et al. (2009 & 2011)	ROP based on Field penetration index (FPI)
Khademi et al. (2010)	ROP based on Field penetration index
Frough et al. (2013)	TBM down times related to rock mass condition (U)
Paltinieri et al. (2016)	Introduced reduction factor and proper distinction of ground classes and fault zones, AR
Dudt et al., (2016)	Introduced penalty factor on rock mass parameters, AR
Maleki (2017)	ROP
Salimi et al (2017)	ROP
Farrokh (2018)	Underestimates the downtimes and overestimates the U

As can be seen in this table, there are several models currently used for prediction of ROP, and to some extent they are reasonably accurate and reliable and account for most of the related parameters. This is in contrast with the models for prediction of U, which are limited number, not reliable, and often with significant errors (Table 1.2).

Table 1.2 TBM Utilization estimation models

Effective Items on utilization / Models		CSM, 1991	NTNU, 2016	QTBM, 2000	RME 07	Farrokh, 2012	Laughton, 1998	Abd-Al Jalil, 1998
Ground condition	RQD	Yes	No	Q Parameters	No	Yes	Yes	No
	Uniaxial compressive strength	Yes	No	Rock mass strength	Yes	Yes	Yes	No
	RMR	Yes	No	Q Parameters	No	Yes	No	No
	Q	No	No	Q Parameters	No	No	No	Yes
	Ground water	Yes	No	Q Parameters	Yes	Yes	Yes	Yes
	Abrasion	Yes	Yes	Yes	No	Yes	No	No
	Cutter change	Yes	Yes	CLI	No	Yes	No	Yes
	Joints orientation	No	No	Q Parameters	Yes	No	Yes	No
	Ground support			Implicit	Yes	Yes	Yes	Yes
Geometry of tunnel	Tunnel curves	Yes	No	No	No	Yes	No	No
	Tunnel diameter	Yes	f(cutter life)	Yes	Yes	Yes	Yes	No
	Slope	Yes	No	No	No	Yes	No	No
	Tunnel length	Yes	Yes	Deceleration gradient (m)	Yes	Stroke length	Yes	Yes
Machine specifications	Thrust	Yes	No	Implicit	No	Implicit	No	Yes
	Torque	No	No	No	No	Implicit	No	No
	Cutter head power	No	No	No	No	No	No	Yes
	Cutter head RPM	No	f(cutter life)	CLI	No	Implicit	No	No
Logistic and Management	Surveying	Yes	Yes	No	No	Yes	No	No
	Logistics	Yes	Yes	m	No	Yes	No	Yes
	Haulage	Yes	Yes	No	No	Yes	No	Yes
	TBM maintenance	Yes	Yes	m	No	Yes	No	Yes
	Back up maintenance	No	Yes	No	No	Yes	No	No
	Labor delay	Yes	Yes	m	No	No	No	No
Re-gripping		Yes	Yes	m	No	Yes	No	Yes
Skill level		No	Yes	No	Yes	Yes	No	Yes
*f(….)= function								

The most prominent models for estimation of TBM utilization are the Colorado School of Mines (CSM) model developed by Sharp and Ozdemir (1991), the NTNU prediction model

developed by Bruland (1998) with addition of tunnel length as a factor by Macias (2016), a statistical and probabilistic model by Laughton and Nelson (1998, 1999), a discrete event simulation model and analytical model by Abd Al-Jalil (1998), the Q_{TBM} model by Barton (2000), the rock mass excavatability index (RME) by Bieniawski (2007), and empirical models by Frough et al. (2013) and Farrokh (2012). Many of the existing models for prediction of U do not show sensitivity to many of the changes in the input parameters and cannot incorporate the new components on the machine or in the backup system. This means that they are rarely used, and new approach is needed to offer a more reliable prediction method that can incorporate site specific information.

1.2 Research objective

The main objective of this research is to develop a flexible and reliable model for estimation of TBM utilization that encompasses the various site set ups and tunneling activities and their interrelationship. The following are the specific objectives of the dissertation:

I. Establishing the time distribution of main activities involved in TBM tunneling, using database from different tunneling projects.

This objective is achieved by gathering the time allocated for different tunneling activities during construction from various projects and prepare time distributions for further input in the simulation model. For activities where measured time distributions are not available, a fix number or anticipated distribution will be assigned based on assumptions and engineering judgement. This allow incorporating the stochastic nature of these activities in the estimates.

II. Development of a TBM performance simulation model capable of estimating Utilization factor based on stochastic interactions between different resources and activities.

This objective is achieved by preparing a simulation model using a DES approach, where the time distributions obtained from objective "I" will be used as input. Arena© DES software is used to prepare the model with different tunnel activities. The relationship and sequence of activities should be defined in this model to allow for simulating the sequence of activities that occur on a jobsite and logical relationship between the activities for TBM advance cycle (Parallel & Linear). The results of modeling will be compared with available field data for verification.

III. Conduct a parametric sensitivity study to assess the effect of various tunneling activities on machine utilization and validate the concept by comparing the results with those of field observations.

This objective could be achieved by analyzing the results of the simulation model with the recorded activities and resulting machine utilizations from different sites. By including the site setting in the modeling one can observe the interaction between various tunneling activities. The percentage contribution of each activity in total downtime will be analyzed and bottlenecks in the performance of the machine will be identified as a function of allocated resources. The comparison of the final output of simulation in terms of estimated utilization time, with the observed TBM utilization in various project will facilitate the verification of the model's accuracy and potential deviations.

Comparing the rock types, RMR values, and the location of various formations along the tunnel, the simulation will be performed to examine the sensitivity of the simulations to geological setting of the site. This allows the assessment of the applicability of the model for estimating TBM utilization in tunnels with various geological settings. Also, a similar comparison with the machine specification and backup system allows or evaluating the impact of individual component or setting (i.e. transportation) on the overall performance of the TBM in a tunneling operation.

IV. Prepare a uniform data collection system for recording the pertinent information on the various tunneling activities for utilization estimation

This objective is achieved by preparing a user interface using visual basic for applications (VBA) to analyze the data and derive the activity times for future DES modeling of TBM operations.

1.3 Tasks performed

The research objectives were met by performing the following tasks:

i. *Performing extensive literature review on TBM performance prediction models to examine the advantages and disadvantages of the existing models.* Review of the prominent methods of performance prediction used in industry and their accuracy in predicting ROP and utilization factor was a part of this step and provided a basis for comparing the result of proposed models with the field observations and estimates by existing models.

ii. *Compiling a database TBM field performance from various tunneling projects and subsequent analysis. This includes identifying important tunneling activities that can be used as input parameter in the simulation models and development of time distributions for various tunneling activities.* In order to develop a model that is capable of estimating utilization TBM factor in different geological conditions and machine specifications, database of various activities in tunneling projects where TBM is used was needed to be further processed as input for the discrete event simulation models. Considering geology as one of the main factor that influences the boring time, the downtimes and delays related to ground conditions had to be quantified, in addition to many other activities in the operation to see the interaction between these activities with the assigned duration based on stochastic distribution to observe and assess their impacts on machine utilization.

iii. *Developing a model using a discrete event simulation software (Arena©) which incorporates various tunneling activities as components of the operation.* Discrete event simulation (DES) software is used to prepare models with the capability to consider each activity as a discrete event and also evaluate the impact of changes in the composition or duration of the activities on overall operation. This includes activities pertinent to a given TBM type in particular sequence that is unique to that machine type an site stting. The model is capable of tracking the advance of TBM on stroke by stroke basis.

iv. *Verification of simulation results by comparing the results of DES modeling with the actual or observed TBM field performance.* The results of the model are compared with the compiled field data in step ii to verify the results of simulations.

v. *Examination of sensitivity of the DES models to different site setting and logistics to evaluate the interaction between different tunneling activities and their impact on overall TBM operation and resulting machine utilization.* The interaction between different tunneling activities was evaluated based on defining various tunneling scenarios to see the staggering effects of delays caused by various activities that are related to specific geological sequence and site settings. This was done by performing sensitivity analysis based on parametric study of different input parameters and resulting machine performance (i.e. various transportation system, utility installation, ground support installation, etc).

vi. *Preparing user interface using Visual Basic for Applications (VBA).* The implementation of various input parameters models were made using an interactive and dynamic data exchange system between the Visual Basic for Applications (VBA) and Arena© model to provide a general platform with easier user interface to be used for practical applications for the industry.

vii. *Developing a MATLAB code to validate the Arena© model.* Finally, a MATLAB code was written for DES modeling of TBM operations and comparison of the results with Arena© was made for validation purpose. The MATLAB code would have limited capabilities but offers easier user interface to add and modify the operational parameters for DES modeling.

1.4 Thesis organization

The thesis comprises of ten chapters. These chapters are technical paper manuscripts that have been published, or are under review, or will be submitted for publication in peer-reviewed technical journals / conferences in near future. This is an acceptable format for graduate thesis based on Graduate School requirement at Colorado School of Mines. Therefore, each chapter has its own abstract, introduction, main body, results and conclusions. This means that there is some level of repetition in the introduction and background portion of these chapters.

The Chapter 2 proposes a simulation model for a specific project which is verified for another project in similar conditions. This chapter is published in *Tunneling and Underground Space Technology (TUST)*. The third chapter compares the various performance prediction models by estimating utilization for eight projects. The revision of this chapter is submitted to TUST and is included in the thesis. Chapter 4 proposes a uniform simulation model wherein the time distributions of various activities are proposed that are based on the available data of nine projects in hard rock. The effect of variability in ground condition on muck transportation system is analyzed in Chapter 5 which is published in the *World Tunneling Conference (WTC), 2019*. The effect of variation in the geology-related delays are assessed in Chapter 6 wherein the results of six projects obtained from simulation are compared with the actual site data and the most critical ground troubleshooting measures are identified. The Chapter is under review in *Acta Geotechnica*.

The simulation results for sensitivity analysis is given in Chapter 7 which is published in *TUST*. Combining the data for nine projects to prepare a data template is part of Chapter 8 which will be submitted to a tunneling focused journal. Finally, the implementation of data template in the simulation code generated using MATLAB is given in Chapter 9 wherein the comparison with the CSM2020 model prepared using Arena© is given. The conclusion of the overall study is given in Chapter 10 along with future recommendations.

CHAPTER 2

PREDICTING TBM UTILIZATION FACTOR USING DISCRETE EVENT SIMULATION MODELS

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2.1 Abstract

Improving the accuracy of models for tunnel boring machine (TBM) performance prediction and estimation of utilization factor is the focus of many ongoing studies in mechanized tunneling. Utilization factor is controlled by tunnel geology, rock mass condition, and size of the tunnel, as well as tunneling activities such as maintenance, utility installation, transportation, surveying, unexpected breakdowns and miscellaneous downtimes. In this study, modeling tunneling activities and downtimes using discrete event simulation approach is used to predict TBM utilization factor and advance rate. Two mechanized tunneling projects were considered for the development of the model and verification of the results. A database was developed using Karaj Water tunnel project to generate the time distributions for various tunneling activities required as input for simulation model. Arena© software was used for the simulation of TBM operation in this project. The result of modeling was used to simulate Nowsood tunnel project for verification.

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The results showed a good correlation between the predicted and observed machine utilization. Hence, the model can predict utilization based on available data for the ground conditions, operational settings, and tunneling activities.

Keywords: TBM, Utilization factor, Simulation, Tunnel

2.2 Introduction

With the advancement of technology, Tunnel Boring Machines (TBM) are widely used in tunneling projects all over the world. Prediction of the TBM advance rate is a very important issue, as it has a big influence on the duration and the cost of the project. TBM performance refers to rate of penetration (ROP), utilization factor (U) and advance rate (AR). Utilization factor is one of the key performance parameters that links the AR and ROP. Most of the available prediction models have only focused on penetration rate estimation. However, a small subset of models such as CSM, NTNU, and QTBM offer some relationships and charts for estimating utilization factor. These models have been under development since the early 1960s and their capabilities have improved based on recent advancement in TBM tunneling and increasing cases, where machines are introduced to ever more challenging ground conditions. However, the estimated utilization factor using the above-noted models are not very reliable or accurate, as these models do not account for many of the critical items such as back up arrangements and site-specific individual tunnel activities. Table 2.1 gives a summary of parameters considered in different performance prediction models. As can be observed, these models are more frequently used for penetration rate estimation. Example of such models and their basis and outputs are listed in Table 2.2. Considering a TBM as a moving tunneling factory, by simulating the main tunneling activities, performance parameters can be easily estimated considering possible time distributions and associated delays.

Some researchers have also applied different soft computation techniques for TBM performance prediction. Benardos and Kaliampakos (2004) correlated TBM performance with geological and geotechnical site conditions by using an artificial neural network. In addition, some TBM performance prediction models were developed based on the fuzzy logic method (Kim, 2004 and Mikaeil et al., 2017).

Table 2.1. Parameters considered in CSM, NTNU and QTBM for Utilization factor estimation

Effective Items on utilization factor		CSM	NTNU	Q_{TBM}
Ground condition	RQD	discontinuities	No	Q parameters
	RMR	Supporting time	No	Q parameters
	Q	No	No	Q parameters
	Groundwater	Yes	No	Q parameters
	Abrasion	Yes	(Pr*)	Yes
	Cutter changing	Yes	Yes	Yes
Geometry of tunnel	Tunnel curves	Yes	No	No
	Tunnel diameter	Yes	No	Yes
	Slope	(In logistic)	No	No
Logistic and Management	Surveying	Yes	Yes	No
	Logistic	Yes	Power extension	No
	Haulage	Yes	Yes	No
	TBM maintenance	No	Yes	No
	Back up maintenance	No	No	No
Re-gripping		Yes	Yes	No

*Pr: Penetration Rate

A discrete-event simulation was used to analyze systems or processes that are very complex and for which analytical approaches do not provide reliable results. Simulation of TBM operation requires incorporating a large database of different tunnel activities and inter-relationship in a way similar to real case scenarios. Simulation approach minimizes the shortcomings in the existing empirical models. The elimination of uncertainties related to cost, time and overall project management are possible by simulation models. Arena© is one of the simulation software used

for industrial purposes. Arena© is an event management software widely used for project management purposes. The software incorporates different activities in terms of different modules that can be interlinked and sequenced. This software is based on SIMAN language, which is a very simple mode of modeling different components of any system. (Davis et al., 1988).

The development or evaluation of complex systems can be done using simulation thereby providing a better understanding of processes (Vieira et al., 2017). Discrete event simulation (DES) is defined as a model to simulate events that occur in sequences presenting its influence on other events. Allen (2011) states that "discrete event simulation and agent-based modeling can offer natural approaches to help people think introspectively about their systems and realize efficiency gains. Because discrete event simulation naturally estimates variation in its prediction, these methods are generally regarded as the starting point for the modelling systems involving high levels of uncertainty that cannot be ignored or "averaged over" in the results." Sharma (2015) mentioned the advantages and disadvantages of simulation and discovered that the DES provides a lot of flexibility thereby proving its capability in a wide variety of applications like the simulation of computer network, business process, data implementation, vehicle manufacturing, transportation modes and traffic issues among others. Discrete event simulation was used for various systems likes job-shop scheduling by Vieira et al. (2017); comparing the energy consumption of a manufacturing system with actual measurements for better understanding and assessment of energy flow (Kouki et al., 2017); assessing the delay in patient transit at major hospitals by Furian et al. (2018); evaluating the supply levels of blood in hospitals during mass casualty events based on London bombing in 2005 (Glasgow et al.,2018) and integrating 3D visualization components to simulate movement of mobile cranes at construction site for planning site layout (Elnimr et al., 2016).

Some examples of simulation in tunneling include development of MiSAS module using DES by Dang et al. (2018) that analyses different processes in microtunneling and identifies the effect of different soil composition on its performance; optimizing productivity and cost of muck disposal in tunnels by integrating input from construction equipment detection model into WebCYCLONE simulation software (Kim et al., 2018).

Some attempts have been made to simulate mechanized tunneling activities in order to predict utilization factor and TBM advance rate. Rostami et al. (2014 and 2016) applied different approaches in the modeling of the tunnel operation using a hard rock TBM. One approach was based on discrete event simulation using Arena©, which is a software commonly used in industrial engineering for simulation of the interaction between various components in a production line. The proposed approaches for simulation of the TBM operation were based on detailed activity time distributions for the rail transportation system in a tunnel. They considered California switches for different scenarios and a variable number of trains to show the possibility of further optimizing the location of the switches in the tunnel. Rahm et al. (2012) introduced a multi-method simulation model for estimating TBM advance rate. Scheffer et al. (2015) worked on the influence of disturbances in mechanized tunneling. They considered disturbance of production processes, disturbance of support processes and cascading effects as three sources of delays that might lead to TBM downtime. Zhang et al. (2016) developed a hybrid simulation approach that integrates a dynamic default tree and discrete-time Bayesian network for TBM performance prediction. Rahm et al. (2016) presented a comprehensive modeling and simulation approach analyzing production and logistics of mechanized tunneling processes. The simulation approach identified bottlenecks and relevant interdependencies among different tunneling activities that were verified by data obtained from three completed metro projects. However, the integration of different ground

conditions, operation parameters, and maintenance delays were neglected which can show significant changes in the estimation of utilization factor.

Table 2.2. Summary of TBM performance prediction models in the literature

References/Models	Methods	Result
Roxborough and Phillips (1975)	Theoretical/Experimental	Normal and rolling force of V type cutters
Graham (1976)	Empirical	ROP (mm/rev)
Ozdemir, CSM(1977)	Theoretical/Experimental	Cutter force
Farmer et al. (1980)	Empirical	ROP (mm/rev)
Snowdon et al. (1982)	Theoretical/Experimental	Cutter force (V type)
Sanio (1985)	Theoretical/Experimental	Normal force of V type cutter using LCM
Sato et al. (1991)	Theoretical/Experimental	Normal force of V type cutter using RCM
Innaurato et al. (1991)	Empirical	ROP (m/h) based on RSR
Rostami and Ozdemir, CSM (1993)	Theoretical/Experimental	Cutter force (CCS disc), ROP, U and AR
Nelson et al. 1983	Experimental /statistical	Performance or ROP based on data base and simulation approach
Palmstrom (1995), RMi	Empirical	ROP
Bruland (1998), NTNU	Empirical	ROP, U and AR
Barton (2000), Q_{TBM}	Empirical	ROP, U and AR
Yagiz (2002), MCSM	Empirical/Experimental	ROP
Bieniawski (2007), RME	Empirical	Advance rate
Yagiz (2008)	Empirical	ROP based on field data
Gong and Zhao (2009)	Empirical	ROP based on field data
Hassanpour et al. (2009 & 2011)	Empirical	ROP based on Field penetration index
Khademi et al. (2010)	Empirical	ROP based on Field penetration index
Frough et al. (2013)	Empirical	TBM downtimes related to rock mass condition (U)

* CSM: Colorado School of Mines, MCSM: Modified Colorado School of Mines, RMi: Rock mass index, RME: Rock mass excavation index, NTNU: Norwegian University of Sciences and University, FPI: Field Penetration Index

In this study, tunneling activities and down times using discrete event simulation approach were modeled to predict TBM utilization factor. The main goal of this modeling exercise was to

simulate the main activities of a mechanized tunnel operation using TBM with different diameter and length that will be excavated through a different type of rock masses. Each type of rock mass can have potential specific downtimes such as TBM stoppage due to rockfall or water flow. Other tunnel activities can be simulated using different time distribution data or equations. To simulate downtimes related to TBM activities, a database was developed based on the study of a mechanized double shield tunnel project. The available database includes drawings, detailed geology, daily shift reports including the length of the excavated tunnel in each rock mass unit, daily boring time, its advance rate and different rock mass related downtimes.

2.3 Methodology

To assess the capability of simulation model, a database from a mechanized tunnel project was used which was reanalyzed to create time distributions for different tunnel activities. Both deterministic and stochastic time distributions were generated from the database to represent various activities that occur for the machine to advance every stroke. Stochastic time distributions were made using Arena© input analyzer that gives the best fitting curve for the data. The distributions were chosen in order to have the best fit based on the lowest square root error. The time distribution obtained for different activities were then set as input parameters in the simulation model.

The simulation model prepared in Arena© was based on the flowchart shown in Figure 2.1. The numbers in blue dots correspond to the modules prepared in the simulation model as shown in Figure 2.3. Delays due to difficult ground, segment installation and re-grip, extension of utilities, unexpected breakdown, cutter change, transportation, and maintenance were grouped and modeled. The difficult ground related downtimes include delays due to excessive abrasion, crown collapse, instability at face, presence of clay and sticky material, squeezing ground and

groundwater flow (Frough et al., 2013). The utility extension delays include all the water pipe, power cable, and ventilation duct extensions. The transportation-related delays include delay in arrival of the train at TBM backup, derailment, loading and unloading of muck, stacking of segments and others related tunnel transportation issues. Daily maintenance, cleaning and inspecting TBM equipment and other maintenance aspects are grouped in maintenance delay. These delays were introduced based on the number of strokes. It should be noted that at this stage, not all the delays in tunnel activities were optimized or stochastic. This means that for some lower ranked activities, a place holder was considered with a constant activity time for future follow up works to focus on each of these items based on field measurements.

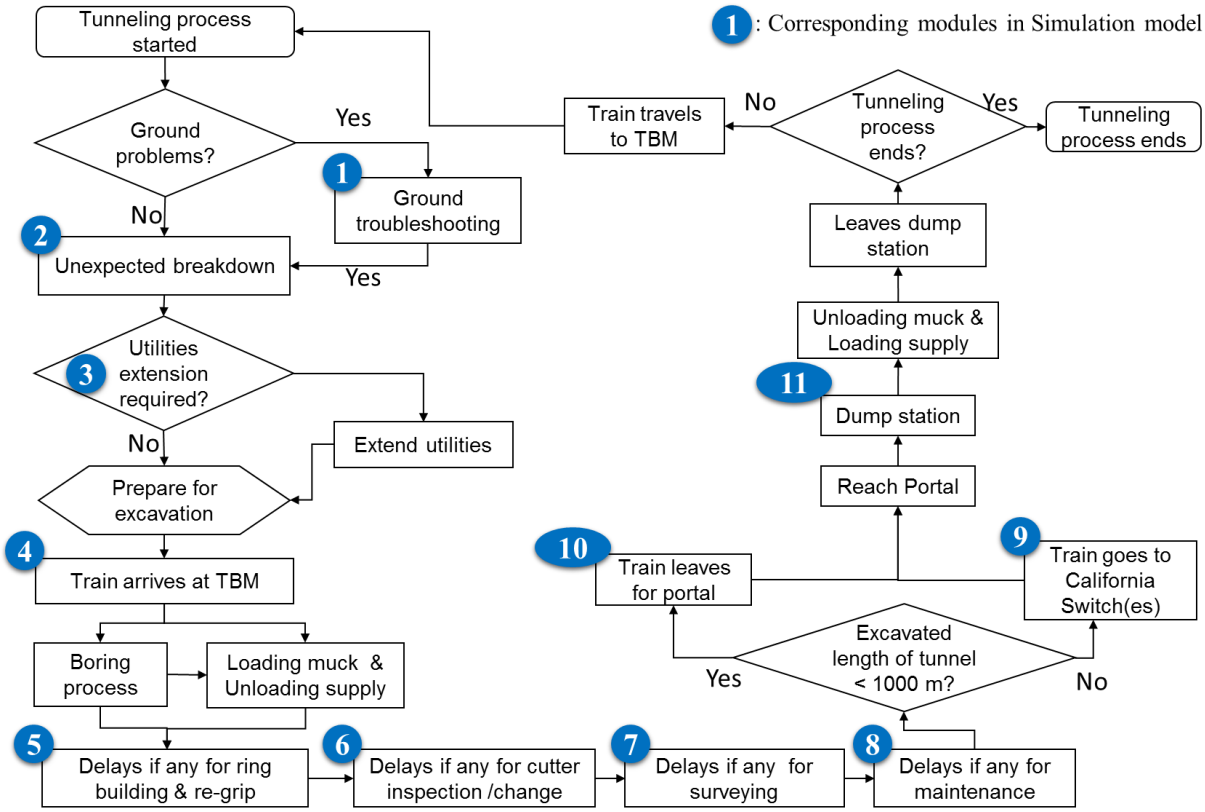

Figure 2.1. Flowchart showing Simulation model

The model was executed for a total number of strokes and U, ROP, and AR was recorded for each geological unit. To examine the stochastic behavior of the simulation model, results for ten replications were combined and resulting distributions for completion time are thereby provided. This methodology gives a range of values that can be procured for the given geological setting and distance from tunnel face and incorporates the relevant uncertainties in the result. Furthermore, the weighted average of utilization factor for each geological unit along the tunnel alignment was obtained and was further compared with the actual data collected from the project site.

2.4 Case studies

Two mechanized tunneling project were considered for developing the database and verification of the simulation model. Both projects were constructed using double-shield TBM. The Karaj–Tehran water conveyance tunnel (KTWCT) with 30 km length is in northwest of Tehran, Iran. The 16 km lot 1 was excavated and lined by a double shield TBM. The boring and final diameter of the tunnel were 4.66 m and 3.90 m, respectively. The tunnels were lined with 25 cm thick pre-cast concrete segments in 5 + key arrangement (Frough and Rostami, 2014).

In the lot 1, the first 140 m was excavated by roadheader and TBM was launched after the end of starter tunnel and served through a portal. The maximum overburden in lot-1 was 670 m, with an average of about 400 m. Developed database achieved from all rock mass units from chainage 163 m to 15724 m were taken for the analysis. The lithology of this area consists of a sequence of Karaj formations and a variety of pyroclastic rocks, often interbedded with sedimentary rocks. The characteristic rock type is green vitric to crystal lithic tuff, tuff breccias, sandy and silty tuffs with shale, siltstone, and sandstone. The formations are classified into 10 engineering geological units as listed in Table 2.3. (SCE, 2004; Hassanpour et al., 2009).

Table 2.3. Engineering geological units encountered along the KTWCT alignment (Hassanpour et al., 2009)

Rock mass unit	Av. UCS (MPa)	Av. RQD	Av. RMR	Remarks on rock properties and descriptions
Gta1-1	55	15	35	Weak to moderately strong rock, thin to moderately bedded, fractured, may be unstable
Gta1-2	100	22	50	Moderately strong rock, thin to moderately bedded, fractured, may be unstable
Gta2	75	45	49	Moderately strong, thick to moderately bedded, moderately fractured, stable
Gta3	100	70	64	Moderately strong, thick to moderately bedded, moderately fractured, stable
Gta4	150	95	75	Very strong thick to moderately bedded, stable
Sts1	120	60	57	Weak to moderately strong rock, thin to moderately bedded, fractured, may be unstable
Sts2	150	85	72	Very strong, thick bedded, stable
Mdg	50	70	63	Moderately strong, thick to moderately bedded, moderately fractured, stable
Tsh	90	50	46	Weak to moderately strong rock, thin - moderately bedded, foliated, fractured, may be unstable
Cz	15	15	21	Very weak strength, unstable rock

In order to develop time distribution for TBM activities, KTWCT project (lot-1 length: 16 km) was studied in detail and available data were reanalyzed to obtain the relevant information for machine performance in various formations as well as different tunneling activities. Tunnel length was divided into 18 units based on the occurrence and sequence of different geological units along the tunnel alignment. Table 2.4 shows the summary of performance parameters for the 18 different units.

Table 2.4. TBM performance in different units based on geology and time distribution classification for KTWCT project

No	Rock mass unit	Length (m)	ROP (m/h)	AR (m/d)	U (%)
1	gta1-1	45.55	0.92	3.25	14.68
2	cz	38.85	1.09	1.05	4.02
3	gta1-2	2211.06	3.29	17.70	22.43
4	gta1-2	308.82	3.78	18.17	20.04
5	gta2	1988.68	3.94	22.60	23.89
6	gta-3	1518.52	3.88	19.98	21.44
7	Sts-1	347.31	4.30	26.72	25.91
8	Sts-2	291.24	3.99	20.80	21.73
9	gta-3	188.55	4.04	23.57	24.31
10	Sts-1	900.82	4.86	20.02	17.15
11	Sts-2	288.6	4.00	14.43	15.02
12	Sts-1	630.45	4.33	12.36	11.89
13	gta-2	1070.26	3.93	15.97	16.94
14	sts-2	759.09	3.76	16.50	18.30
15	gta-4	3513.63	3.52	13.67	16.20
16	Sts2	418.72	3.78	14.44	15.90
17	Tsh	598.48	3.50	13.60	16.19
18	Mdg	442.32	4.09	16.38	16.68

To examine the capability of the simulation model for use in prediction of potential TBM performance in similar projects, the database from Karaj project was used for performance prediction of the Nowsood tunnel project. Nowsood water conveyance tunnel was about 50 km long. Lot-1A of this project was of 14 km in length and was excavated and lined using a double shield TBM. The tunnel has a boring and final diameter of 5.28 m and 4.5 m, respectively.

The lithology of Nowsood lot-1A area consists of a sequence of Jurassic-cretaceous formations containing limestone, shale and clay-limestone (SCE, 2008). Table 2.5 shows the rock mass data of geological units based on the study of area along the tunnel profile. Performance parameters obtained from the site are summarized in Table 2.6. This table does not cover the entire

14 km of tunnel, rather the sections where the information has been reliable and verified. The basic machine specifications of the TBMs for both the tunnel projects are given in Table 2.7.

Table 2.5. Average Rock mass parameters in different rock mass units for Nowsood project (SCE, 2008)

Rock mass unit	Av. UCS (MPa)	Av. RQD	Av. RMR	Remarks on rock properties and descriptions
LI1	75	62	39	Strong, thick-bedded, stable
LI2	125	62	49	Strong, thick-bedded, stable
LI3	125	62	49	Strong, thick-bedded, stable
LI-SH1	125	82	36	Weak to moderately strong rock, moderately bedded, fractured, may be unstable
LI-SH2	125	62	40	Weak, thin bedded, fractured, approximately unstable
LI-SH3	37	70	56	Weak, thin bedded, fractured, approximately unstable
LI-SH4	20*, 75**	62	46	Strong, thick-bedded, stable

*Shale ** Limestone

Table 2.6. TBM performance in different units based on geology and time distribution classification

No	Rock mass unit	Length (m)	ROP (m/h)	AR (m/d)	U (%)
1	LI-SH1	3728.68	3.43	13.33	10.97
2	LI1	265.86	3.60	13.36	11.56
3	LI2	437.07	3.83	22.64	20.81
4	LI-SH2	154.66	3.88	27.66	25.78
5	LI-SH3	539.02	3.77	29.79	26.95
6	LI3	332.01	3.84	30.01	27.67
7	LI-SH4	411.55	3.81	25.02	22.86

2.5 Simulation of TBM activities

The developed database from Karaj project was used for the development of time distributions. The database for each delay was obtained in terms of time/day. In addition, the site engineers had performed some time studies on various aspects of tunneling and related tunnel activities that were available for this study and has been analyzed. This includes the analysis of variation of duration for each activity that has been plotted in related histograms to fit the best distribution function for estimation of the given activity in the simulation model. The simulation model was set up to offer time distribution on basis of the number of feet mined or stroke, therefore the units were modified to show hr/stroke. The data in hr/stroke was analyzed to generate time distributions for each tunnel activity. "Arena Input Analyzer" was used to make the time distributions for the critical activities. Figure 2.2 show some examples of time distribution obtained from Arena input analyzer. The time distributions were also analyzed for various geology and distance from the portal to see the sensitivity of different activities to changes in geology and length of the tunnel.

Table 2.7. Specifications of TBMs for the 2 tunnel projects

Specification	Karaj Lot-1	Nowsood Lot-1A
Machine diameter (m)	4.66	4.527
Disc diameter (mm)	432	432
Disc / cutter spacing (mm)	70	70 to 75
Number of cutters	31	38
Cutterhead power (kW)	1,250	1,750
Max. Cutterhead speed (RPM)	11	10.8
Max. Cutterhead torque (kNm)	2,500	2,472
Max. Cutterhead thrust (kN)	17,000	20,400

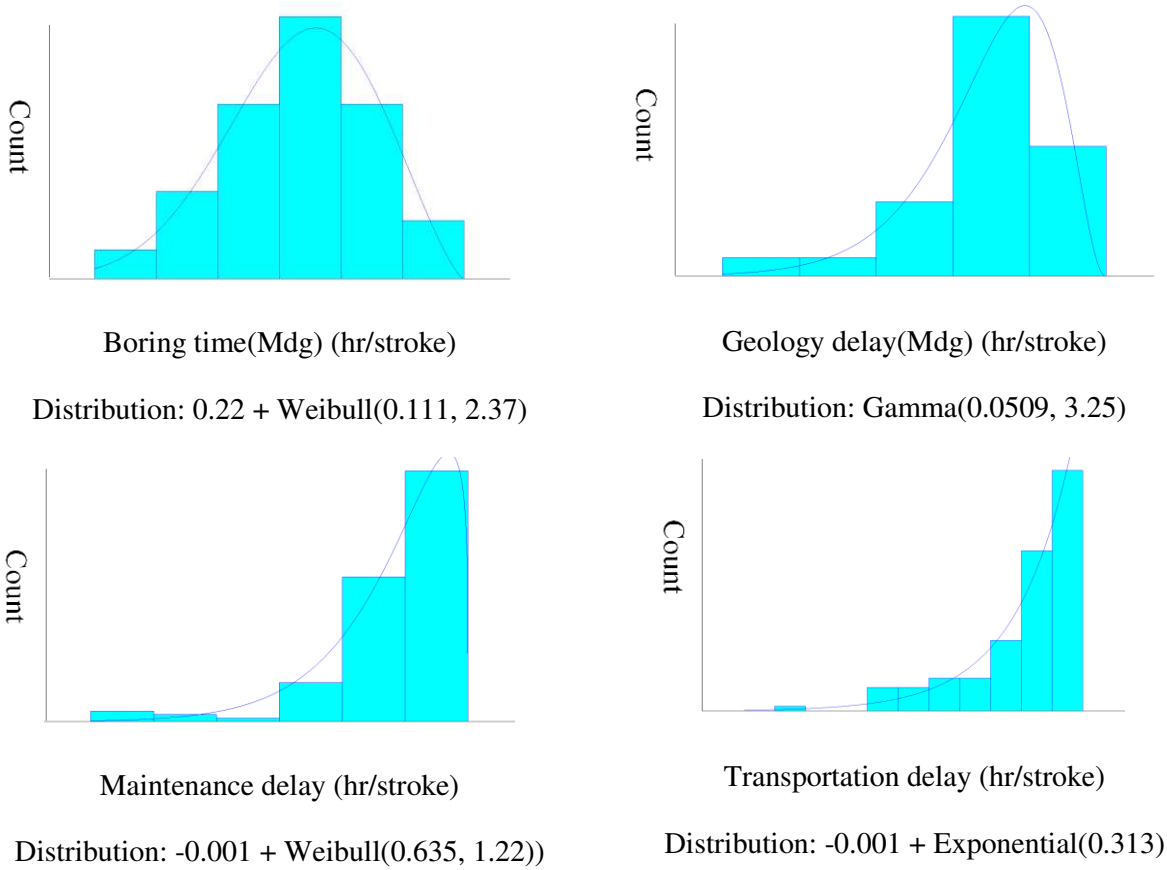

Figure 2.2. Time distribution examples from Arena© Input Analyzer

Arena© software was used for simulation of TBM activities for KTWCT project, based on the flowchart shown in Figure 2.1. The time distribution for whole tunnel length was divided into two types. The first type was based on 18 different geological units along the tunnel alignment as shown in Table 2.4. The second type was based on the dividing tunnel length into eight 2000 m segments. The time distributions discussed before was used and the results of simulation for each activity was analyzed. These simulations were based on 24 hours of working time. Non-working days were not taken into account. The initial 163.27 m of the tunnel length was ignored as the initial 140 m was excavated by conventional method and a certain length of the tunnel was considered part under the learning curve. The frequency of different tunnel activities was assumed

as per the site data. A total of three California switches were installed and each of them was activated with increasing distance in the model. The number of trains was also increased with the tunnel length from one to four. The simulation model defining tunnel activities and their connections are shown in Figure 2.3. The connections were done using a route module in the software.

A normal distribution for total number of days for excavation was generated considering 10 replications and it was seen that the total number of days varied from 940 to 1049 days with an average of 984 days. The actual time for excavation was 975 days (Figure 2.4). Comparing it with the average value, variation of 1% or 10 days was observed thereby presenting an acceptable correlation between the model and the real case scenario.

The eighteen models made for the eighteen geological units along the tunnel alignment were executed with ten replications for each section. The critical path affecting the utilization factor in the TBM operation was also assessed. For example, the number of trains used for muck disposal and supply of components affected the utilization factor as the excavation had to wait for train arrival at the heading, therefore increasing the stoppage time. So, this could be considered as the critical path for higher length of TBM tunnels. The observed average utilization factor came to be 19.8% against actual of 19.1% (Figure 2.5).

2.6 Applicability of the model for other projects

In order to evaluate the applicability of the model for other tunnel projects, the same Arena© model with the time distributions developed from data of KTWCT project was used for the simulation of Nowsood project. Comparing the RMR values, time distributions for ground-related downtimes and boring were determined for the different geological units. For other tunnel activities, tunnel length was the basis for assigning different time distributions. The first 505.21 m

of tunnel length was not considered for the analysis as the excavation for this length was assumed to be under the learning curve and therefore, implementing values from Karaj project for this tunnel length was not realistic. A tunnel length of 5.86 km was considered for the analysis, where detailed information was available. The actual tunnel project used conveyor belt as a muck transportation system and the train was used only for the supply of components.

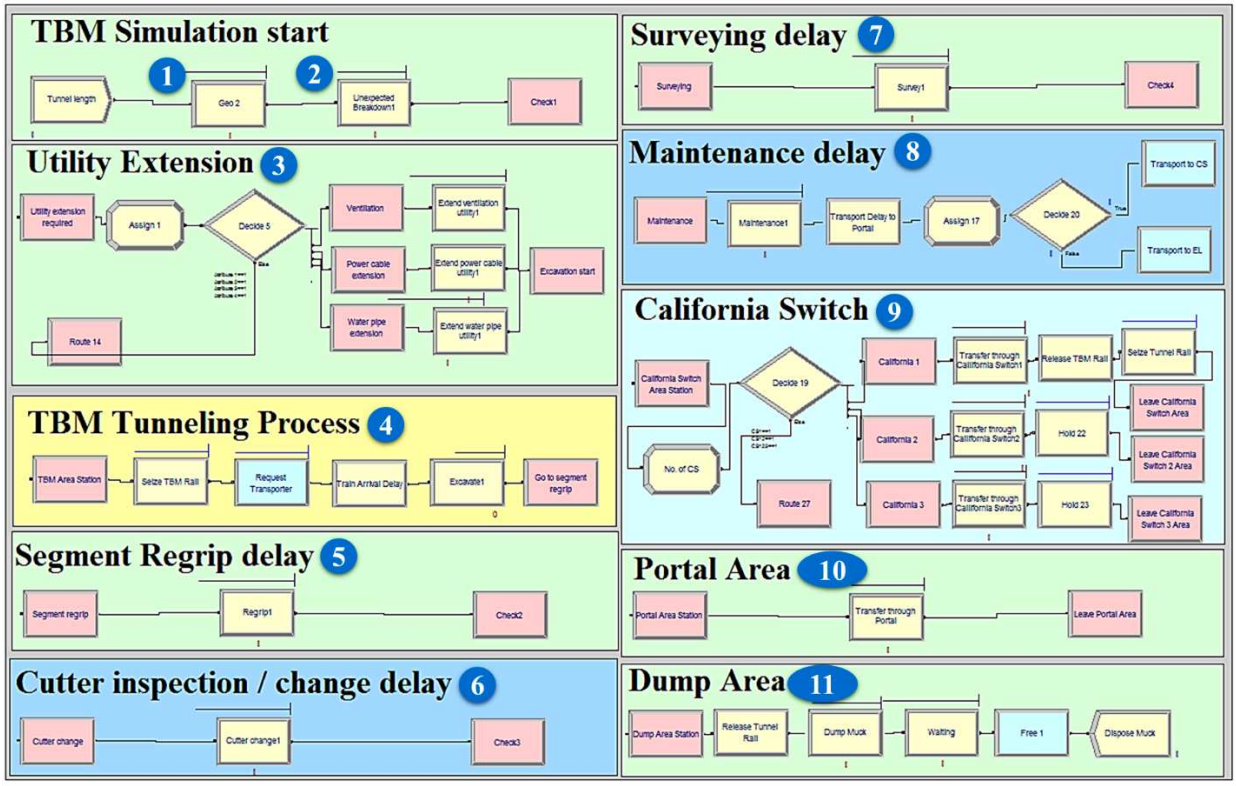

Figure 2.3. Screenshot of Arena© Simulation model for Karaj tunnel

The simulation results show that the model was applicable for Nowsood project as shown in Figure 2.6 to Figure 2.8. The distribution of U for ten replications are given in Figure 2.9. The inconsistency in the result can be attributed to the complex geology at these locations. The utilization factor obtained from simulation was 13.3% against the actual 15.3%. Usage of conveyor

belt for muck transportation in the actual scenario was considered. However, the effect of change of muck transportation from a conveyor belt to train cannot be seen in the results. The reason for this can be the transportation of supplies by train being critical path for this tunnel project.

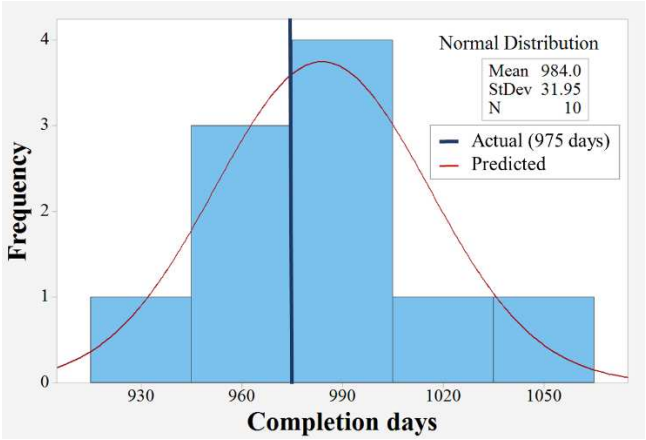

Figure 2.4. Normal distribution showing completion time obtained from simulation and from site

2.7 Discussion

The simulation model was prepared for Karaj project and used for modeling of TBM performance in Nowsood project to assess the applicability of the model. The results from the model show good correlation between the actual and predicted ROP, AR and U. The comparison chart for Karaj project given in Figure 2.5 shows that the variation in the values between actual and predicted data are acceptable. The comparison between predicted and observed machine utilization in Figure 2.6 shows a good correlation between predicted and actual values. Hence, the applicability of the model for the operation of similar TBM type in a different tunnel project is feasible. The comparison between the actual and predicted data as shown in Figure 2.7 gives a higher correlation coefficient for Karaj project than for Nowsood project that may be attributed to

wide geological variation. However, the overall average variation of utilization factor for Karaj project is significantly less as shown in Figure 2.8.

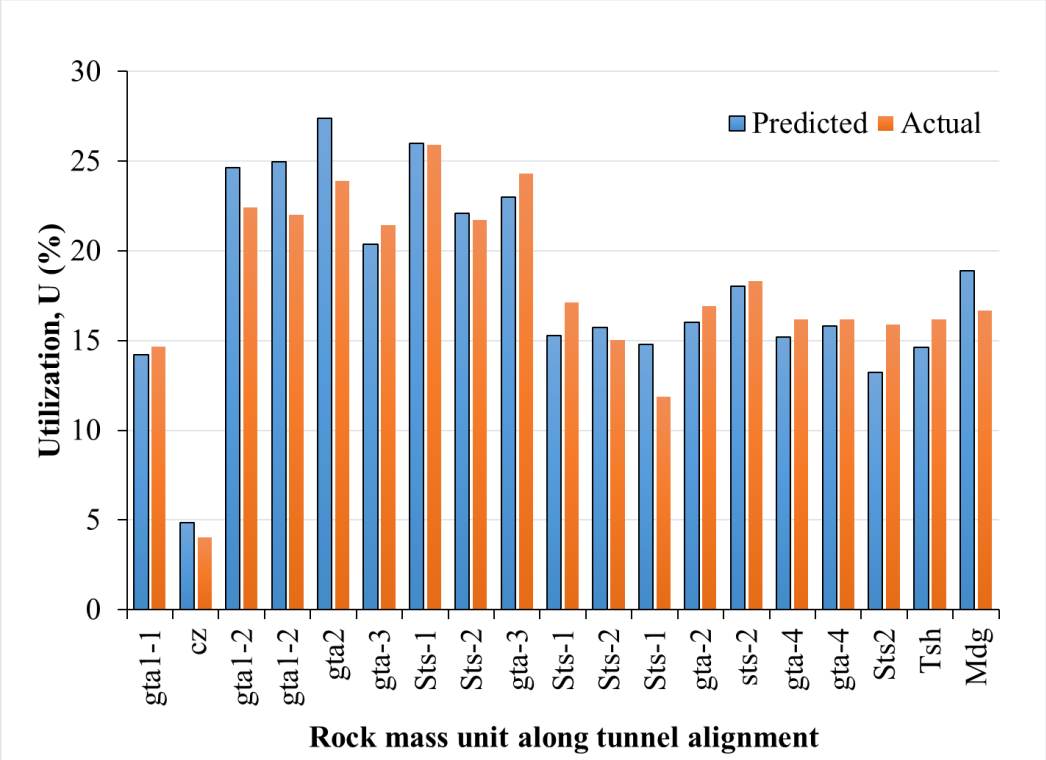

Figure 2.5. Comparison of utilization factor for Karaj project (from 163.27 m to 15724.22 m)

The results from ten replications of the simulation model were used to obtain probable distribution of machine utilization as shown in Figure 2.9. This distribution with additional values like average, minimum, maximum and standard deviation can be extracted for the overall performance prediction of the TBM operation. As can be observed, the histograms are not bell-shaped, so they do not necessarily follow normal distribution. Part of the reason for this is the limited number of replications or the special setting of the site, machine, and geological sequence. This issue will most likely be mitigated by increasing the number of repetition or better definition of activities and related time distributions. It can also be noted that more accurate results can be

obtained with the incorporation of more details of tunneling activities and increasing the number of replications for each simulation.

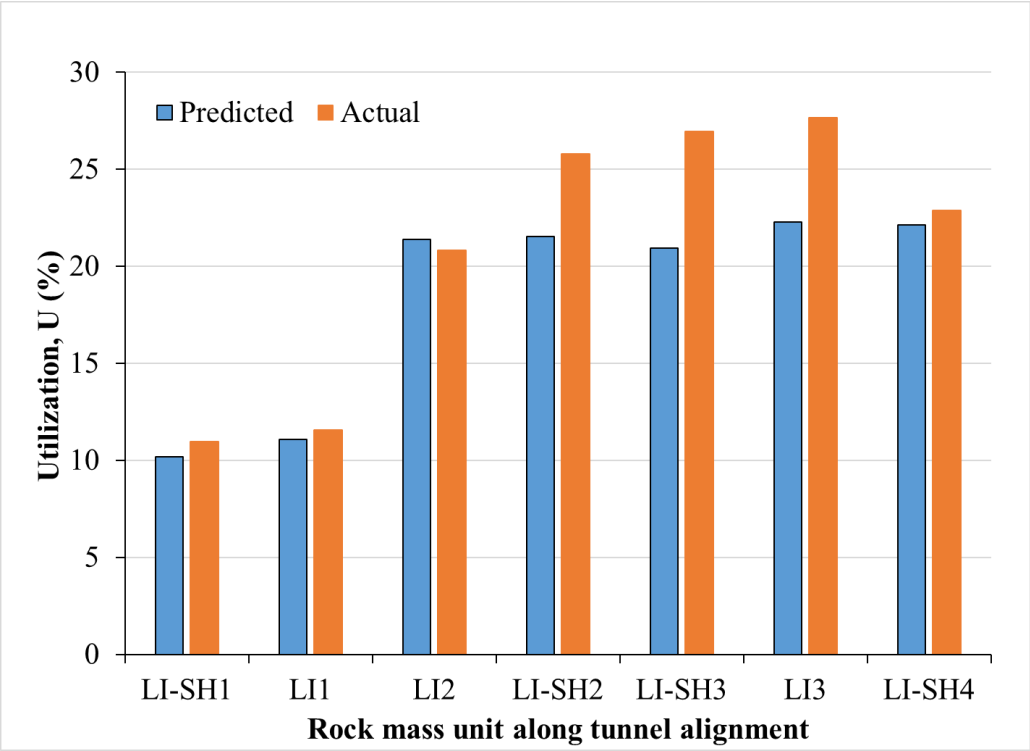

Figure 2.6. Comparison of utilization factor for Nowsood project (from 505.21 m to 6374.06 m)

Another source of difference in the results of modeling is that the boring diameter of Karaj tunnel was 4.66 m as compared to 5.28 m for Nowsood tunnel. The sensitivity in the results due to TBM diameter needs further studies and was not considered in this round of simulation.

The muck transportation used in Nowsood tunnel was conveyor belt as compared to the rail system in Karaj tunnel. The utilization factor can most likely vary due to the usage of different muck transportation system. However, in the case of Nowsood tunnel, the train used for the supply of utilities and segments were on the critical path and therefore the contribution of conveyor belt

related delays in overall performance of TBM operation was not significant. This also shows that if the project had used the rail system for muck transportation, notable additional delays could be anticipated. However, it should be noted that the simulation of Nowsood tunnel was done for a certain length of the tunnel (5.5 km) and with increasing distance from the portal, the effect of using conveyor belt and potential for increasing transportation delays could become more pronounced.

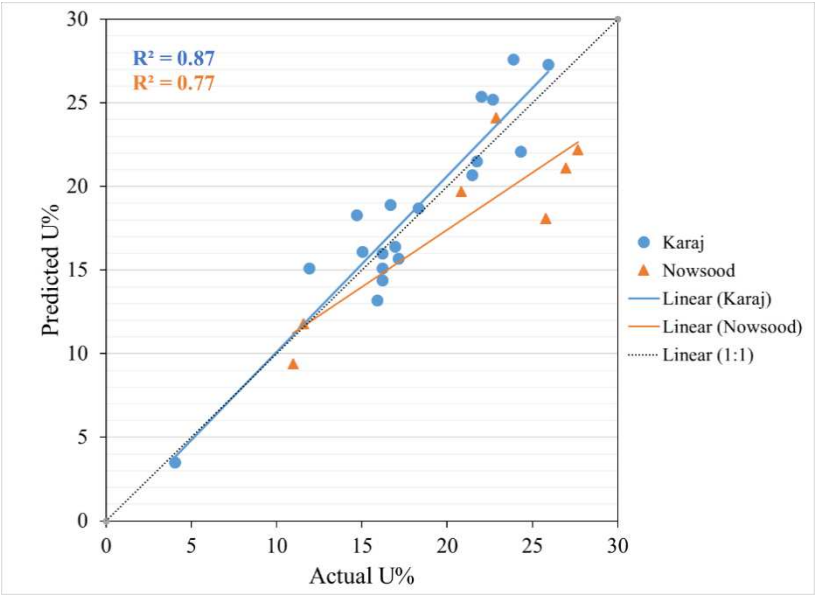

Figure 2.7. Co-relation between predicted and actual data for Karaj and Nowsood project

The experience of the operators and tunneling crew plays an important role in TBM operation especially during the initial phase of tunneling. Incorporating this aspect in the simulation was difficult due to limited availability of data and hence was not considered. A larger database is required to include other factors such as launching system (shaft/portal), machine size, back up arrangements, machine types, crew experience, etc. to obtain a better perspective on related factors related to the site set up and human influence on the operation. These factors can

be incorporated into the models using discrete event simulation and cannot be easily accounted for in other models, especially the existing empirical models.

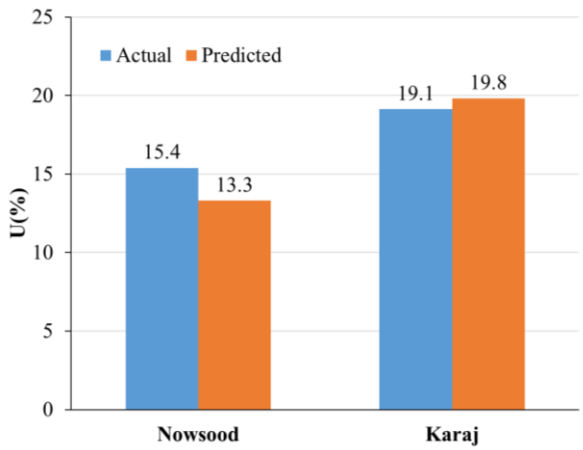

Figure 2.8. Average utilization factor comparison for Karaj and Nowsood project

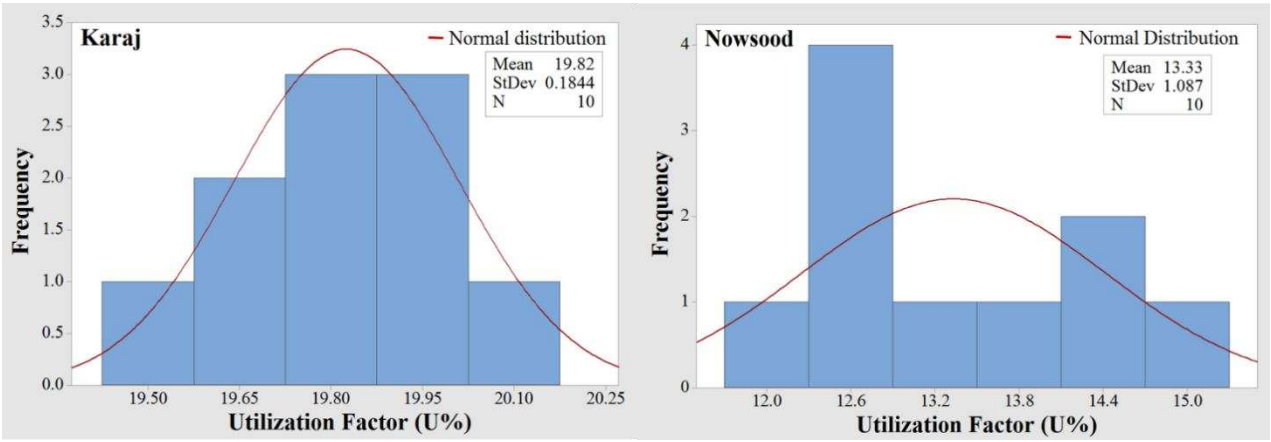

Figure 2.9. Distribution of utilization factor for Karaj and Nowsood project

2.8 Conclusions

The focus of this paper is to examine the potential of discrete event simulation (DES) in predicting TBM utilization. In this study, data from Karaj water conveyance tunnel project (lot 1) was used to generate relevant time distributions for various tunneling activities, which were subsequently used as input parameters for modeling TBM performance using DES approach. The results show that the utilization factor obtained from simulation and those from the site were having an average variation of +/-1%. To assess the applicability of the model for predicting machine utilization in other projects, a 6 km section of Nowsood tunnel project was used in the simulation and the results were examined. The time distributions were considered by comparing similar geological unit and length of the tunnel. The estimated values for average utilization were comparable as the variation in utilization factor from actual and predicted data came to be 13.3% instead of 15.4%. The results of the study show that the simulation model predicts the utilization factor that is comparable with the actual data.

Hence, it can be concluded that discrete event simulation is a reliable method of predicting the TBM performance. This refers to the concept that is applicable to TBM tunneling, versus the models used in this study which was machine and site-specific. For generalization and use in other operations, proper number and sequence of activities should be incorporated in the simulation models. At the present, the simulation model can use RMR to represent the rock mass conditions, while other rock mass classification system can be considered and used to represent ground conditions for estimation of the utilization factor for other tunnel projects. The simulation model was prepared considering the tunneling activities for a double shield machine and is applicable for any other similar project. The time distributions of different tunneling activities will be different based on the machine size, site setting, and contractor experience. Ground related delays could

only be applied to similar geological conditions, but a different setting could be considered for other projects and anticipated features and obstacles. The effect of the difference in TBM types, tunnel diameter, alignment, and contractor's experience can be integrated into the simulation model as part of the planned activities and related time distributions for a project in the future. Further development of the model considering the above-listed issues will provide more realistic simulations and predicted utilization factors. Additional work is underway to make the simulation models universal and applicable to a variety of TBM types and ground conditions.

2.9 Acknowledgments

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CHAPTER 3

COMPARISON BETWEEN DISCRETE EVENT SIMULATION APPROACH AND VARIOUS EXISTING EMPIRICALLY-BASED MODELS FOR ESTIMATION OF TBM UTILIZATION

3.1 Abstract

The fundamental components in predicting the TBM performance (advance rate) are rate of penetration and utilization. Extensive studies have been conducted to accurately estimate these parameters. Inclusion of various tunneling activities and their interdependencies, the impact of site set up and management, and the role of human factors on the operation makes estimation of utilization a complex task.

A few models have been developed to predict machine utilization, and these models are based on statistical analysis of available TBM project databases. Apart from the existing models, use of discrete event simulation (DES) for estimation has also been examined for TBM performance prediction. The sensitivity and accuracy of all these prediction models demonstrate strong influence of geological conditions and site settings. The present study compares outcome predictions from six empirical models and DES simulations for eight projects. The variability of the predictions is assessed, and the prediction outcomes are tested for "validation" by comparison with results from the recorded observation at the tunneling sites.

The result showed that the difference between the predicted utilization using discrete event simulations and actual value available from site data was 7%. Comparing the utilization obtained from other empirical methods, considerable deviation can be seen. Hence, it is concluded that the DES approach provides for more accurate estimation of machine utilization while offering the

flexibility to customize the model on the basis of both equipment selection and the availability of data to incorporate the complex interdependencies of different tunneling activities.

Keywords: TBM, discrete event simulation, excavation, tunnel, utilization

3.2 Introduction

Use of tunnel boring machines (TBMs) is considered as a very common approach for tunneling underground construction projects. Gu et al. (2014) reported on the planned use of over 1000 TBMs just in China for metro expansion by 2020. This unprecedented use of TBMs in infrastructure development points to the need for efficient operation as well as more reliable performance estimation models, especially for machine utilization. The key element to achieve a higher performance is the skillful selection of equipment, workforce training, design of the site set up and management of logistics associated with TBM operation. Innovation in TBM operation and the consequent prediction of excavation system performance has become a necessity in today's tunneling industry. This is a challenging task that needs to incorporate the contributions of many individual tunneling activities to accurately predict the performance of the whole excavation system.

The performance prediction of TBM has always been an issue of high interest for the industry that is generally measured in terms of progress or advance rate. Many different approaches have been taken to estimating the rate of penetration (ROP), utilization (U) and advance rate (AR) of the machine. Utilization is defined as the percentage of shift time during which excavation or rock penetration occurs (Nelson, 1983). Accurate estimation of utilization requires complete knowledge of the TBM and backup system as well as all contractor activities during tunneling and their sequence, and the skill / experience of the crew and project management. While TBMs are often very productive machines, the reality is that rarely is the TBM utilization over 50%, and for

many jobs, the TBM utilization is in the 20-30% range (Rostami, 2016), indicating that the machine is not excavating a majority of the time, and the excavation is often halted by some form of downtime. A list of typical downtime categories and their relative importance was given by Nelson (1983). This list provides a framework for estimation of the expected downtimes for the TBM tunneling projects in this study, with quantitative data presented for each category. It is notable, however, that the prediction models developed over past decades fail to encompass all these factors qualitatively or quantitatively, thereby compromising the accuracy of the estimates.

Several performance prediction models are available, e.g., Frough et al. (2019); Delisio et al. (2013); Duhme (2017); Yagiz (2008); Frough et al. (2015); Hamidi et al. (2010); Xue et al. (2018); Farrokh (2012). However, very few have demonstrated the capability to reliably predict the TBM utilization. The most prominent models for estimation of TBM utilization are the Colorado School of Mines (CSM) model developed by Sharp and Ozdemir (1991), the NTNU prediction model developed by Bruland (1998) with modification to include the effect of tunnel length as a factor by Macias (2016), a statistical and probabilistic model by Laughton and Nelson (1998, 1999), a discrete event simulation model and analytical model by Abd Al-Jalil (1998), the Q_{TBM} model by Barton (2000), the rock mass excavability index (RME) by Bieniawski (2007), and empirical models by Frough et al. (2013) and Farrokh (2012). The accuracy of determination of utilization is highly dependent on the inclusiveness of the accounting of time incurred in maintenance involving performance of numerous activities at TBM face and back-up area, geology-related activities and other site-specific events. An overview of utilization for rock TBMs was offered by Rostami (2016), and this source includes general range of machine utilization based on machine type, complexity of the site geology, and muck transportation system.

Decision Aids for Tunneling (DAT) is a method based on discrete event simulation (DES) for estimating the total cost of tunnel and the total construction time including the uncertainties related to geologic conditions, construction processes and resources (Einstein, 2002; Einstein et al. 2017). The performance of equipment, the crew efficiency and unanticipated construction events lead to uncertainty in the predicted advance rate. This variability is encompassed in the DAT analysis as it provides a range or a cloud of total construction time vs cost using eight components or modules. The modules are exploration, description of geology, design analysis, construction simulation, geologic updating (on the basis of encountered conditions), project and construction management, resource simulation and management and graphics. The exploration component allowed to assess the usefulness of planned exploration which provides the uncertainties of geologic conditions that are further used in other construction simulation and geologic description components. The geologic description component addresses the average length of the geotechnical units and its transition probability to another unit. Design analysis component focuses on the stress and strain generated due to various cross sections thereby validating its design. Construction simulation component involves various ground classes, tunnel cross sections, initial and permanent support measures as well as excavation methods and is based on Monte Carlo method. The input in terms of cost and advance rate distributions are to be defined by the user for each construction class. The "Supervisor" module controls sequencing of different tunnel and shaft sections along with the distance and time-based delays. Construction management module provides a decision-making capability with changing geologic conditions while resource simulation and management module help in simulating factors like human, material, financial, energy and equipment resources during construction (Halabe, 1995). Applicability of DAT in assessing the risk associated with the geological conditions by analyzing the Piora zone in the

Gotthard base tunnel was performed by Dudt et al. (1999). However, the construction related issues were not highlighted. The relevance of DAT is mostly seen in the design phase wherein different tunnel alignments and construction methods can be compared to make an informed decision. For example, understanding construction related uncertainties for determining the project cost for the Sucheon tunnel in Korea performed by Min (2003) and Min et al. (2008). Further elaboration of the method by implementing the sequence of activities and resource allocation to achieve overall reduction in construction cost was performed by Min and Einstein (2016). The method, however, do not identify the critical parameters influencing the overall project duration.

Some observations of these models on the basis of input parameters (revised version of Khetwal et al, 2020) is presented in Table 1.2, and these data clearly indicate the variability of input parameters for each model. Barton (2013) also indicates that a single value of utilization as representative for a given TBM project is misleading as a huge variation in the value is observed at the start of the project during the learning curve, in variable geology and distance of portal from excavation face. Recent advancements in this field have been introduced by Rahm et al. (2016) and Duhme (2014, 2017), and in these studies the components affecting various tunneling activities were specifically addressed to identify the possible bottlenecks and associated delays. These studies, however, did not provide any complete methodology to incorporate all the activities and integration of delays and machine specifications in estimation of utilization. Frough and Torabi (2013) and Frough and Rostami (2018) developed correlations between the rock mass classification and installed support-related downtimes and TBM performance with reasonable accuracy. These relations, however, did not incorporate the effect of other parameters affecting the utilization. Zhang et al. (2016) proposed a hybrid simulation approach combining a dynamic default tree and discrete-time Bayesian network for predicting the performance of a TBM. The

model, however, was validated for only one metro project and requires further assessment to ensure its applicability in the industry.

3.3 Simulation Modeling

Simulation is a very powerful tool for understanding the complexity of design and operations of a system or an operation. Simulation is capable of exploring new resource allocations, identifying bottlenecks, insight on which variables are most important to performance and the interactions among various input parameters (Pegden et al., 1995). Therefore, site-specific explicit modeling of all tunneling activities for prediction of machine utilization seem to be a logical choice.

Stochastic simulation of systems requires considering the underlying randomness in durations of various activities and tasks (Abourizk et al., 2010). Considering the various types of simulation models and analyzing the diversity in the behavior of tunneling activities, a combined model of discrete and continuous events may be formulated. Frough et al., (2019) discussed use of discrete event simulation (DES) for evaluating different tunneling operations. Recently, the potential of discrete event simulation (DES) for utilization estimation was also assessed and shown to be a promising approach (Khetwal et al., 2019). Complexity in tunneling operations was evaluated through examples given by Duhme (2014) wherein the interconnectivity of the logistics and system components at TBM jobsites and its subsequent effect on every operational activity was discussed.

Recent implementations of DES have included assessment of the effect of disturbances and different soil compositions on productivity using AnyLogic by Dang et al., (2018), prediction and evaluation of the performance of variable production line using Arena© by Li et al., (2018), combined study of construction process simulation using WebCYCLONE and vision-based

context reasoning to automate the productivity assessment for an earthmoving process in tunnelling (Kim et al., 2018), and evaluation of different strategies using DES for red blood cell provision during mass casualty events by Glasgow (2018). Abd Al-Jalil (1998) first used discrete event simulation (DES) in estimation of TBM utilization wherein a set of 10 input parameters provided a stochastic distribution of completion time. Simsuper software and FORTRAN code were used to estimate the machine utilization. This approach, however, did not consider all the tunneling activities required for the estimation and mainly focused on the geological variability along the tunnel alignment.

Rostami (2016) and Frough et al. (2019) presented a methodology of predicting the utilization using the DES approach. The delays associated with different tunneling activities were given in terms of their respective time distributions that were analyzed as an integrated system to estimate the utilization. Duhme (2017) used SysML, a DES software to simulate the various tunneling processes. Khetwal et al. (2019), performed similar analysis and observed notable changes in estimated TBM utilization when accounting for the effect of the muck transportation system on the operation given the variable geological conditions along the tunnel alignment. Overall, the use of DES methodology for the estimation of utilization has been proven to be a promising approach considering its accuracy and easy applicability for any TBM project. The study reported here is conducted to assess the accuracy and reliability of various performance prediction models to estimate TBM utilization for eight different tunneling projects.

3.4 Methodology

The purpose of this study was to analyze the uncertainty in using the different performance prediction models and comparing the results to estimate the most efficient prediction methodology. The existing prediction models used for comparison are Colorado School of Mines (CSM) model

by Sharp and Ozdemir (1991), NTNU prediction model by Bruland (1998), updated NTNU model by Macias (2016), Laughton (1998), RME by Bieniawski (2007) and the empirical model by Farrokh (2012). These prediction models were incorporated into a MS Excel spreadsheet, including all related graphs corresponding to respective prediction models. The DES simulation model was prepared using Arena© simulation software and the results are compared with the actual values observed in the case studies. The results of modeling and simulation for estimation of U were initially verified using data from Karaj water conveyance tunnel project, lot 1.The lithology of this area consist of sequence of Karaj formations which is composed of variety of pyroclastic rocks, often interbedded with sedimentary rocks that are mainly green vitric to crystal lithic tuff, tuff breccias, sandy and silty tuffs with shale, siltstone and sandstone (Hassanpour et al., 2009). The details of rock mass units are given in Table 3.5. Ground related issues encountered were rock jamming, rock fallout, water inflow, cleaning muck from cutter head. Hydraulic, mechanical, electrical related delays were combinedly considered as the unexpected breakdown. Transportation delays were also considered into the simulation model that was composed of delays in transportation and unloading of muck, train exchange, derailment, track placement and related issues. The raw database was converted to units of hours/cycle and time distributions were made from them, with the cycle being defined as the stroke of the hydraulic cylinders (1.5 m). These time distributions were fed into the simulation model in terms of activities and delays as per Figure 3.4. A total of 19 simulation models were prepared to account for the effect of tunnel distance from the excavation face to the muck disposal area located at the portal area and addition of California switches with increasing length. The simulation model predicted stochastic distribution of utilization with an average value of 19.8% against the actual utilization of 19.1%. The model was further used to compare the utilization of Nowsood project and average utilization of 13.3 % was

observed against the actual 15.3%. The details of the analysis are given in Frough et al. (2019) and Khetwal et al. (2020). Additional validation of estimated U using the DES simulation approach was performed in this paper by analyzing data for another six projects.

The simulation models were prepared based on the availability of pertinent data from each project that contributed to the utilization estimation. These include the delays due to ground troubleshooting like support installation, TBM and back-up system delays, transportation and other TBM logistic delays. The flowchart used for simulation was made based on the availability of data as shown in Frough et al. (2019). The available databases included the tunnel sub-sections, and these were further processed to obtain the U in terms of individual strokes of the TBM hydraulic cylinders. The recorded times corresponding to different tunneling activities were used to obtain respective time distributions, and these were checked for goodness of fit using chi-square and Kolmogorov-Smirnov tests. The Arena© input analyzer and Minitab® were used to obtain the time distributions that were set as input parameters in the different modules corresponding to the different tunneling activities in the simulation model. The type of time distributions obtained were triangular, exponential, gamma, Erlang, Weibull, beta, lognormal and normal.

The various distributions selected for representing the time allocation of tunneling activities may be attributed to their characteristics. For example, triangular distributions were used in the simulation models where the available field data on specific activities were limited, or where only the minimum, maximum and mode values could be interpreted. An exponential distribution was used to model time for independent events that occurred at a constant interval rate. This mode of distribution has a wide range of applications including the reliability analysis of products and systems, queuing theory and Markov chains (Tamhane and Dunlop, 2000). Exponential and geometric distributions are memoryless, and this limits their application when determining the

system failure due to wear and tear, that causes a cumulative effect. The gamma distribution was used to model positive data that are skewed to the right and greater than zero, as is commonly used in reliability survival studies and representing task completion times. In cases where activity time was an integer, the Erlang distribution was used, which often is used to represent the time required to complete a task. A lognormal distribution was used to represent the positive quantities such as for task times that are skewed to the right, and the bell-shaped curve of the normal distribution was used to represent data ranging from $-\infty$ to $+\infty$, and not for positive values like processing times. The Weibull distribution is versatile, can take various forms and is widely used to represent non-negative task times for systems with many parts that fail independently like happens in a TBM excavation system (Kelton et al., 2013). A set of 50 replicated simulations were done to acquire stochastic distribution of U in each case study. In order to have a separate cycle of generation into adjacent non-overlapping streams of random numbers in each replication, a stream is introduced in every module that is also useful for variance reduction.

The output of simulation model gives a stochastic distribution of U with 95% confidence interval also accounting for the input uncertainty. However, for this study an average value was taken for comparison among the various models for prediction of TBM utilization. The simulation models were subdivided based on the different geological units occurring along each tunnel alignment. The basis of these simulation models is shown as flowcharts in Figure 3.2 and Figure 3.3.

3.5 Case studies

The applicability of the simulation model can be determined by assessing the results for eight different projects. The information of the projects is given in Table 3.2. The details of C11 tunnels, C31 tunnels, Culver-Goodman and Chicago TARP tunnel projects were taken from

Nelson (1983) where open type main beam rock TBMs were used. The detailed plan view and geotechnical cross sections are given in Nelson (1983). Two other projects, the Karaj water conveyance tunnel and the Nowsood project, were added to the analysis to include assessment of projects with double-shield TBMs. The effect of tunnel length was considered in the analysis, but the effect of excavation diameter was not taken into account; however, the diameter variation for these projects was limited between 4.0 and 6.5 m. The data obtained from Nelson (1983) was divided as geology-related delays, TBM and logistics delays and therefore the input in the simulation model was made accordingly (Table 3.2). The actual progress of excavation for the tunnels are given in Figure 3.1. The simulation model shown in Figure 3.4 corresponds to that used for the KWCT and Nowsood projects. Figure 3.5 shows the simulation model for C11-Outbound, C11-Inbound, C31-Outbound, C31-Inbound, C-G and C-T projects. The input parameters for the CSM model by Sharp and Ozdemir (1991), NTNU models by Bruland (1998) & Macias (2016), Laughton (1998), RME by Bieniawski (2007) and Farrokh (2012) models are given in Table 3.1.

Table 3.1. Input parameters considered in the performance prediction models

Type	CSM (1991)	NTNU (1998 and 2016)	Laughton 1998	Rock mass Excavability (RME) 07	Farrokh 2012
Geology & Ground related issues	RMR	RMR		RMR	RMR
	Water inflow delays (hr/m)	Time per cutter change and inspection (h/km)		RME07 = Uniaxial compressive strength + Drillability + Discontinuities in front of tunnel face + Number of joints per meter + Stand-up time + Groundwater inflow+ Orientation with respect to tunnel axis	Downtimes related to unfavorable ground conditions, which needs additional or support or dewatering (h/km)
	Rock support installation delay				Support installation time (planned) (h/km)
	Rock Support Category				Cutter check / change time
					Probing times for ground exploration
					Effect due to quartz content

Table 3.2 Continued

Type	CSM (1991)	NTNU (1998 and 2016)	Laughton 1998	Rock mass Excavability (RME) 07	Farrokh 2012
Tunnel specifications / Geometry	Length of tunnel (m)	Tunnel length (h/km)*	Length (m)	Cumulative tunnel length (m)	Diameter (m)
	Radius of curve (m)			Diameter (m)	Radius of curve (m)
	Direction of tunnel drive (°)			Factor of adaptation to the terrain	Tunnel slope (°)
TBM specification & back-up downtimes	Delays associated with thrust cylinder piston restrike (h/m)	Repair and service of backup (h/km)	Unit downtime (h/m)		Back-up breakdown times (h/km)
	Unscheduled maintenance (h/m)	Repair and service of the TBM (h/km)			TBM breakdown time (h/km)
Utility extension	Utility extension				Utility, line extension times
Survey	Surveying delays for alignment curves (h/m)				Times for changing surveying stations and checking tunnel direction
Re-gripping		Re-gripping (h/km)			Re-grip, Resetting times of TBM after each excavation stroke
Transportation	Tunnel mucking system	Muck transport			Tunnel mucking system, Muck transportation and unloading (hr/km)
Maintenance	Scheduled maintenance (Cutterhead check, TBM lubrication)	Maintenance downtime (h/km)			Routine maintenance of cutter head, TBM and back-up
Others	Labor delays (h)	Miscellaneous activities (h/km)		Qualifications of the tunneling crew & contractor	Unclassified times (Others) (h/km)
				Dispute Resolutions	

*The effect of tunnel length is considered for NTNU 2016 model.

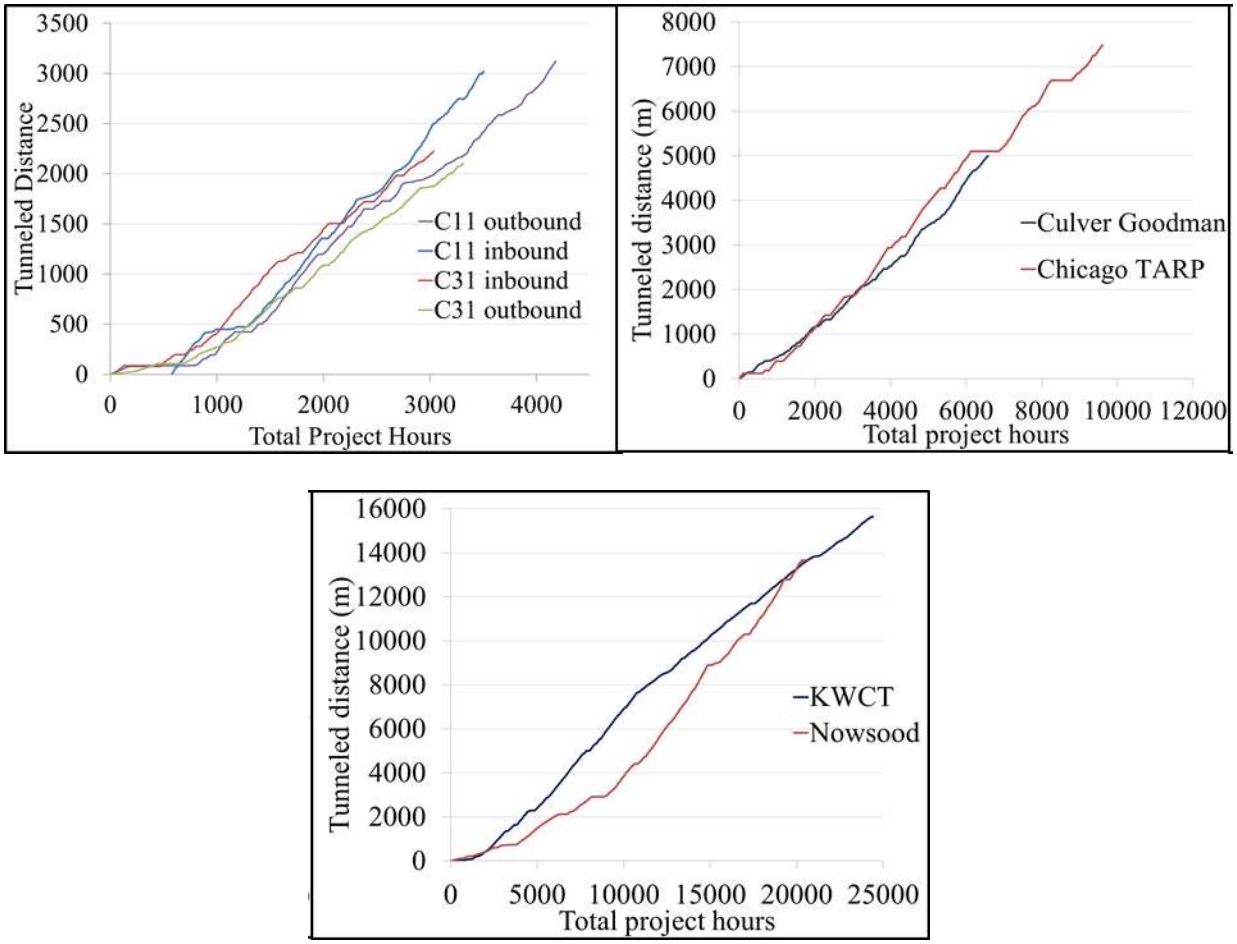


Figure 3.1. Tunneled distance versus cumulative project hours for C11, C31, Culver-Goodman, Chicago TARP, KWCT and Nowsood tunnel projects (Nelson,1983; SCE, 2008; Frough et al., 2019)

Table 3.2. Case records (Nelson, 1983 and Frough et al., 2019)

Project Name	C11 Outbound tunnel	C11 Inbound tunnel	C31 Outbound tunnel	C31 Inbound tunnel	Culver-Goodman tunnel	Chicago TARP	Karaj Water conveyance tunnel	Nowsood project
Project acronym	C11-O	C11-I	C31-O	C31-I	C-G	C-T	KWCT	Nowsood
Place	Buffalo, New York	Buffalo, New York	Buffalo, New York	Buffalo, New York	Rochester, New York	Chicago, Illinois	Tehran, Iran	Iran
Year of construction	March 1980 - November 1980	May 1980 - January 1981	January 1980 - August 1980	April 1980 - November 1980	July 1980 - August 1981	March 1979 - October 1980	2006-2009	Jan 2010 - May 2012
Tunnel length (m)	3,111	3,112	2,076	2,025	5,058	7,261	15,700	13,623
Tunnel diameter (m)	5.6	5.6	5.7	5.6	4.0	6.5	4.65	5.28
TBM type	Open	Open	Open	Open	Open	Open	Double shield	Double shield
Recycle stroke (m)	1.5	1.5	1.5	1.22	1.5	1.83	1.3	1.3
Average U (%)	32	36.2	31.1	28.9	36.1	35.0	19.1	24
Average AR (m/day) for 24 hour period	21	24	18	18.3	18.5	18.7	17.4	20.6
Average penetration (m/hr)	2.8	2.8	2.4	2.6	2.1	2.2	3.8	3.5
Total calendar days	251	217	199	199	381	595	1017	859
Total production days	149	124	130	126	261	385	913	699
Reference	Nelson, 1983	Nelson, 1983	Nelson, 1983	Nelson, 1983	Nelson, 1983	Nelson, 1983	Frough et al., 2019	SCE, 2008

*Nowsood project includes a 14 km long tunnel alignment but for the present study, only the initial 5.3 km was considered in the analysis.

For the C11, C31, Culver-Goodman and Chicago TARP projects, the geology throughout the alignment was considered to be uniform due to lack of division of data with change in geology. The C11 and C31 projects were completed in the Buffalo, New York and their longitudinal profile showed negligible variation in the geologic units throughout the alignment. The main formations in the C11 project are Onondaga, Akron, Bertie and Camillus and the alignment predominantly crosses Bertie Formation having an average uniaxial compressive strength (UCS) value of 166 MPa with an average RQD of 79%. The Bertie Formation lies beneath the Arkon Formation and consists of dolostone, dolomitic limestone and dolomitic shale having thickness ranging from 10.7 m to 18.3 m. There are four members within the Bertie Formation. The youngest, Williamsville, is a hard, massive and fine-grained dolostone with occasional shale beds and thickness of 1.5-2.4 m. The Scajaquada member is 0.9-3.0 m thick, thin-medium bedded, dark gray, dolomitic shale and argillaceous dolostone laminated with thinly spaced bands of dark shale and traces of pyrite. The next member, the Falkirk had thickness of 5.5-7.6 m and consisting of massive, hard, grayish-brown to tan, medium to coarse-grained dolostone with occasional 76-102 mm thick bands of shale. The oldest Oatka member is comprised of 1.5-2.4 m thick medium-bedded, moderately hard, dark bluish-gray dolomitic shale and shaley dolostone. The longitudinal alignment for the C31 contracts shows that the alignment lies in the Bertie Formation well below the highly abrasive Onondaga Formation and above the Camillus Shale Formation which has the potential of water inflow and possible lower strength and fractured rock. The geological profile is given in Nelson (1983). Major geological issues for the C11 tunnels were heavily jointed rock and high water inflow. Major downtimes were due to installation of steel sets, rock jams, scaling, gripper difficulties and clearance of trailing gear. A total of 63 and 60 cutters were changed for the C11 outbound and inbound tunnel excavations, respectively. The C31 outbound tunnel had major

geology-related downtime due to installation of steel sets, as the tunnel was exposed to heavily jointed and weathered rock while for the C31 inbound tunnel, rock bolt drill repair caused major downtimes. A total of 29 and 43 cutters were changed for the C31 outbound and inbound tunnels respectively (Nelson, 1983).

The Culver-Goodman tunnel project in the Rochester, NY area is mined below a sequence of glacial deposits of varying thicknesses. The tunnel is in the lower Paleozoic sedimentary rock units that strike east-west and dip to the south at about 12-15 m/km. The major geology-related downtimes due to presence of heavily jointed rocks in some areas and overbreak in the crown tunnel sections with shale were installation of steel sets, scaling loose rock and removal of muck jams from cutterhead buckets. The presence of highly abrasive rock caused a total change of 810 disc cutters. The details of these stratigraphic units in the project area are given in Table 3.3. The geological profile of the project shows that the tunnel crosses seven stratigraphic units and one major fault. However, tunnel subdivisions were not used in the analysis so the variation of delays and other TBM activities are evaluated as whole-project time distributions including the entire tunnel alignment.

The Chicago TARP tunnel project in the Chicago, IL area is excavated beneath a sequence of glacial deposits and in the underlying Lower Paleozoic sedimentary rocks. The rocks units strike north to north-east and dip to the east or southeast at 1.9 to 2.8 m/km. The project geology generally consists of dolostone and shale deposits of Silurian age. The tunnel alignment lies below the abrasive chert and weathered rock in the Racine Formation and above the Edgewood Formation with predominant excavation in the Markgraf member of the Joliet Formation and the Kankakee Formation (Table 3.4) Accumulation of water at the heading caused major downtime for this tunnel.

Table 3.3. Stratigraphic units for Culver-Goodman tunnel project (Nelson, 1983)

Stratigraphic units for C-G tunnel	Description	Average RQD	Average Unconfined Compressive Strength
		%	MPa
Grimsby	17 m thick, red to green mottled, fine to coarse-grained, well cemented, medium to massive bedded sandstone	94	134
Thorold	0.3-0.9 m fine-grained, cemented sandstone	90	130
Maplewood	4.6-6.4 m thick, green, thinly-bedded shale, calcareous in places	80	65
Reynales	5.1-6.4 m thick limestone with shale interbeds.	83	147
Lower Sodus	4.6-5.5 m thick, thin to medium-bedded fossiliferous shale with occasional limestone seams.	80	74
Williamson	1.8-3.0 m thick, dark green shale with thin limestone beds.	81	82
Irondequoit	4.6-7.0 m thick, light gray, thin to medium bedded, medium to coarse-grained limestone.	91	123

Table 3.4. Stratigraphic units for Chicago TARP tunnel project (Nelson, 1983)

Stratigraphic units for C-T tunnel	Description	Average RQD	Number of joints in 30 m of core	Average Unconfined Compressive Strength
		%		MPa
Markgraf	10 m thick, light to medium and bluish-gray, fine-grained dolostone, frequently mottled. Moderately argillaceous and silty with shale in upper and middle parts.	96	2.0	174
Kankakee	8.5 m thick, white to gray, fine to medium-grained, thinly bedded dolostone with green shale.	95	1.6	153

The details of Karaj and Nowsood project have been presented by Frough et al. (2019). The Karaj project is excavated in green vitric to crystal lithic tuff, tuff breccias, sandy and silty tuffs with shale, siltstone and sandstone. The lithology for the Nowsood project excavation

comprises of limestone, shale and clay-limestone. The available data for the projects were classified on the basis of different geological section or rock units therefore analysis was divided accordingly for the Karaj and Nowsood projects. The details of the geotechnical units of the two projects are given in Table 3.5 and Table 3.6 respectively.

Table 3.5. Engineering geological units encountered along the Karaj water conveyance tunnel project (Hassanpour et al., 2010, Khetwal et al., 2020)

Rock mass unit	Lithology	Av. UCS (MPa)	Qualitative Term (BS EN ISO 14689-1:2003 (2004))	Av. RQD	Av. RMR	RMR rating	Remarks on rock properties and descriptions
Gta1-1	Light cream lithic and vitric tuff, sandstone, siliceous tuff	55	Strong	15	35	Poor	Weak to moderately strong rock, thin to moderately bedded, fractured, may be unstable
Gta1-2	Light cream lithic and vitric tuff, sandstone, siliceous tuff	100	Strong	22	50	Fair	Moderately strong rock, thin to moderately bedded, fractured, may be unstable
Gta2	Sandstone, green vitric tuff and siliceous tuff	75	Strong	45	49	Fair	Moderately strong, thick to moderately bedded, moderately fractured, stable
Gta3	Sandstone and micro-conglomerate	100	Strong	70	64	Good	Moderately strong, thick to moderately bedded, moderately fractured, stable
Gta4	Siliceous green tuff and sandstone	150	Very strong	95	75	Good	Very strong thick to moderately bedded, stable
Sts1	Massive green tuff, tuffy siltstone, sandstone and micro-conglomerate	120	Very strong	60	57	Fair	Weak to moderately strong rock, thin to moderately bedded, fractured, may be unstable

Table 3.6 Continued

Rock mass unit	Lithology	Av. UCS (MPa)	Qualitative Term (BS EN ISO 14689-1:2003 (2004))	Av. RQD	Av. RMR	RMR rating	Remarks on rock properties and descriptions
Sts2	Green vitric and lithic tuff, siltstone, siliceous green tuff and sandstone	150	Very strong	85	72	Good	Very strong, thick bedded, stable
Mdg	Monzodiorite, Monzogabbro	50	Medium strong	70	63	Good	Moderately strong, thick to moderately bedded, moderately fractured, stable
Tsh	Alteration of thin bedded shale, siltstone and sandstone	90	Strong	50	46	Fair	Weak to moderately strong rock, thin -moderately bedded, foliated, fractured, may be unstable
Cz	Crushed zone	15	Weak	15	21	Poor	Very weak strength, unstable rock

Table 3.6. Average Rock mass parameters in different rock mass units for Nowsood project (Frough et al., 2019)

Rock mass unit	Av. UCS (MPa)	Av. RQD	Av. RMR	Remarks on rock properties and descriptions
LI1	75	62	39	Strong, thick-bedded, stable
LI2	125	62	49	Strong, thick-bedded, stable
LI3	125	62	49	Strong, thick-bedded, stable
LI-SH1	125	82	36	Weak to moderately strong rock, moderately-bedded, fractured, may be unstable
LI-SH2	125	62	40	Weak, thin-bedded, fractured, approximately unstable
LI-SH3	37	70	56	Weak, thin-bedded, fractured, approximately unstable
LI-SH4	20 (shale), 75(limestone)	62	46	Strong, thick-bedded, stable

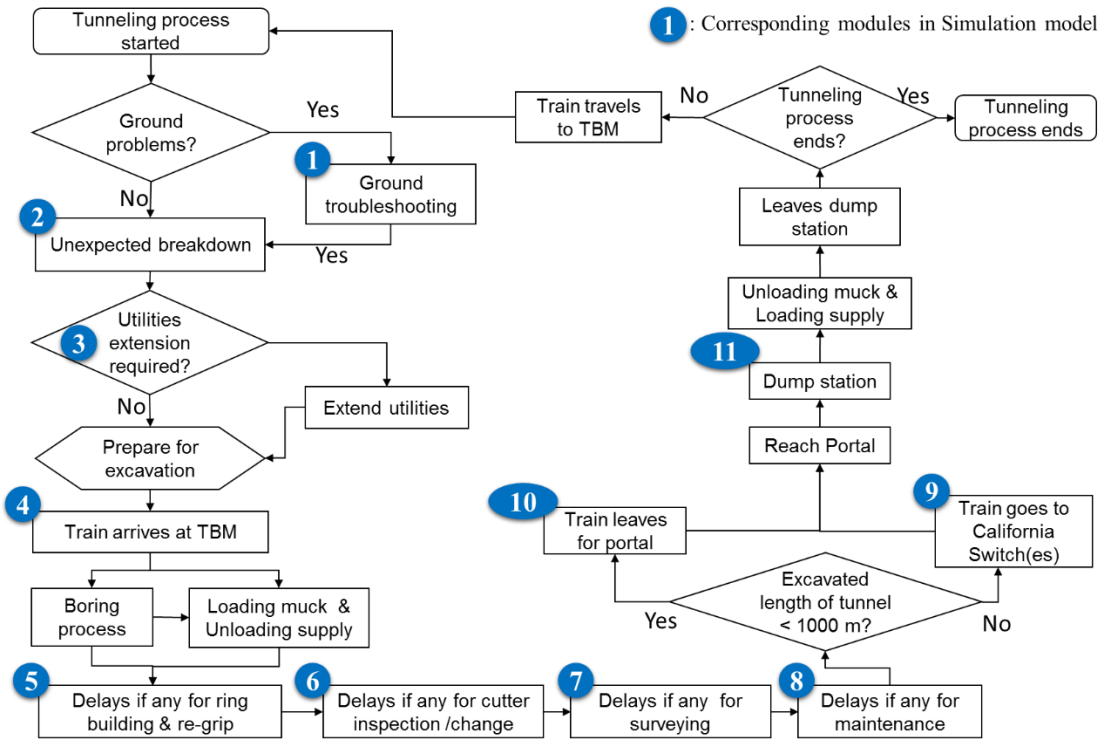


Figure 3.2 Flowchart-1 for the KWCT and Nowsood project

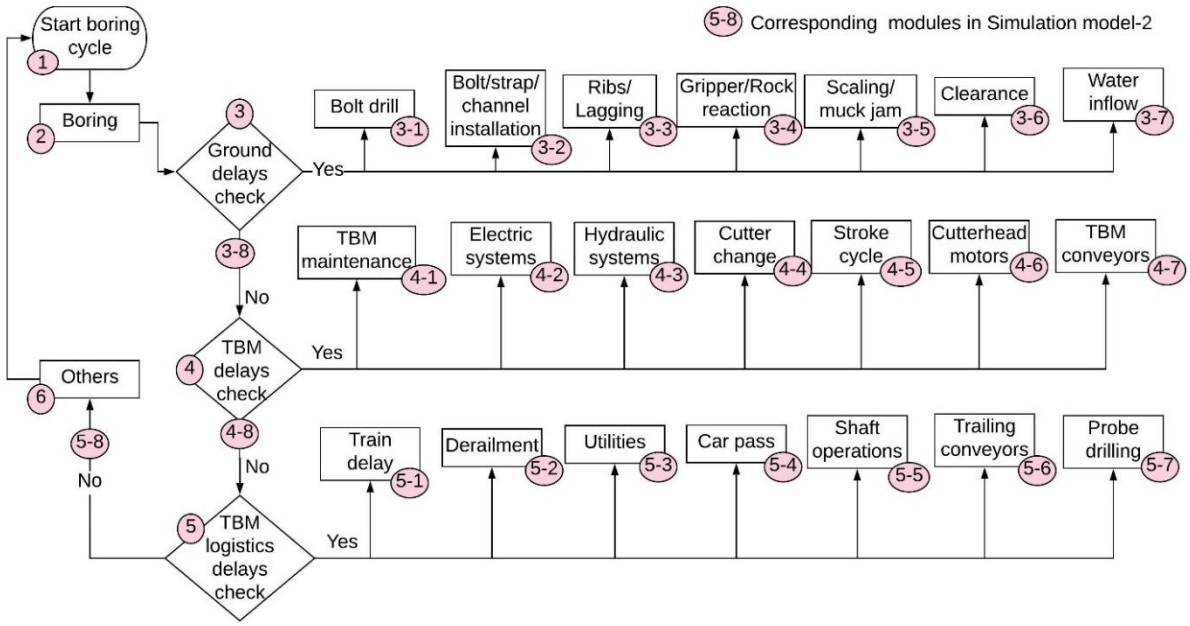


Figure 3.3 Flowchart-2 for the C11-I, C11-O, C31-I, C31-O, C-G and C-T as given by Nelson (1983)

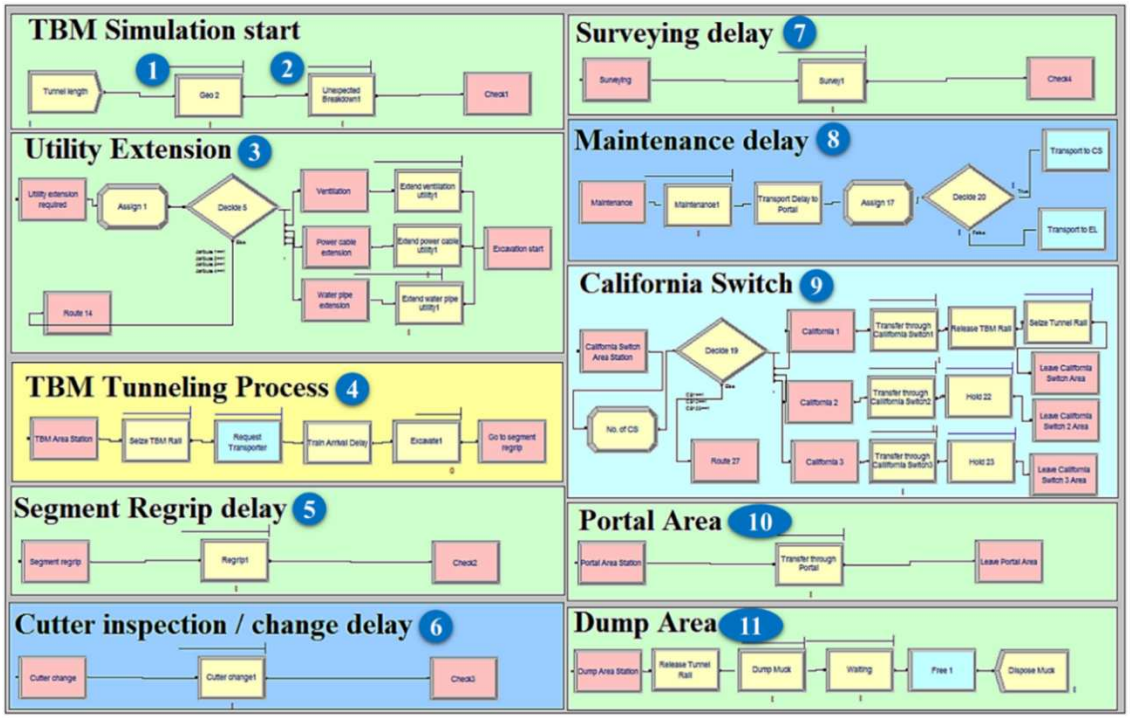


Figure 3.4. Simulation model-1 for the KWCT and Nowsood project

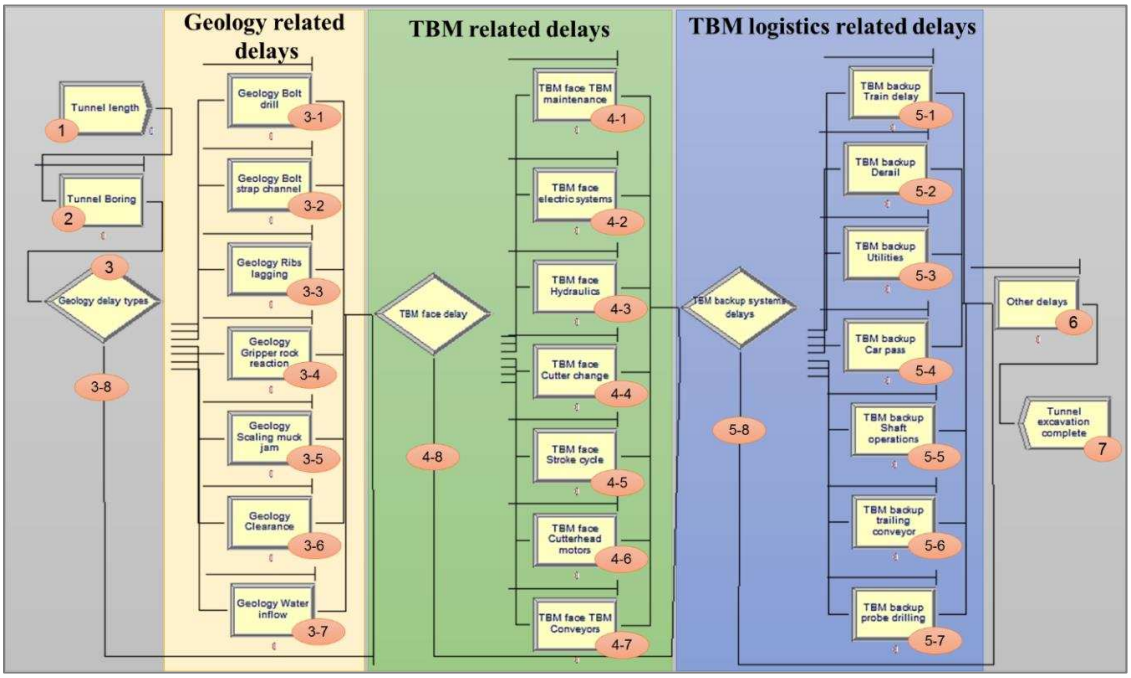


Figure 3.5. Simulation model-2 for the C11-I, C11-O, C31-I, C31-O, C-G and C-T projects

3.6 Analysis and results

The analyses for C-11, C31, Culver-Goodman and Chicago TARP tunnels were based on the time studies obtained from Nelson (1983), as raw data directly from project site were not available. Some assumptions were made to estimate unknown input parameters required for the performance prediction models on the basis of suggestions from experts. The Rock Mass Rating (RMR) value as input for the Rock Mass Excavability (RME) model was calculated on the basis of joint frequency interpreted from the geological description provided for the projects. For the Karaj and Nowsood projects, available raw data from project site was processed for this study. For all the projects, the cutter life index and drillability rate index were estimated from the database given in NTNU reports (Bruland, 1998).

Table 3.7. Comparison of U for the eight tunnel projects.

Projects	Actual U	CSM 1991	NTNU 1998	Laughton 1998	RME 2007	Farrokh 2012	NTNU 2016	Simulation
C11-O	32	43 (34%)	40 (25%)	50 (56%)	23 (-28%)	32 (0%)	36 (13%)	32 (0%)
C11-I	36.5	45 (23%)	40 (10%)	50 (37%)	22 (-40%)	32 (-12%)	36 (-1%)	35 (-4%)
C31-O	31.1	43 (38%)	43 (38%)	53 (70%)	29 (-7%)	36 (16%)	38 (22%)	29 (-7%)
C31-I	28.9	41 (42%)	39 (35%)	51 (76%)	27 (-7%)	35 (21%)	35 (21%)	26 (-10%)
C-G	36.1	47 (30%)	44 (22%)	56 (55%)	41 (14%)	40 (11%)	42 (16%)	35 (-3%)
C-T	35	45 (29%)	44 (26%)	55 (57%)	35 (0%)	41 (17%)	43 (23%)	34 (-3%)
KWCT	19.1	34 (78%)	29 (52%)	47 (146%)	28 (47%)	34 (78%)	25 (31%)	19.8 (4%)
Nowsood	24	37 (54%)	31 (21%)	46 (92%)	25 (4%)	29 (21%)	29 (21%)	17 (-29%)
Overall variation		41%	30%	74%	15%	22%	19%	7%

NOTE: Calculated U and (variation)

The comparison of predicted versus actual values of U for the eight projects is shown in Table 3.7 considering 24 hours as working time per day. The values in the parenthesis shows the

percentage variation in relation to the actual value. A negative value means that the simulation model underestimated the utilization. Comparing the overall accuracy of the performance prediction models for the eight projects, the DES simulation results show only 7% variation from the project-achieved performance, while all other models had variation of more than 14%. The RME method by Bieniawski (2007) showed variation of 15% while the updated NTNU model by Macias (2016) had overall overestimation of 19%. Similarly, the CSM model by Sharp and Ozdemir (1991), NTNU model by Bruland (1998), Laughton (1998) and Farrokh (2012) methods consistently overestimated the TBM utilization. The RME typically underestimated the utilization (Figure 3.6). Some of this variation can be attributed to the models being outdated, and incomplete in terms of not including some tunneling activities that contribute to the utilization estimation.

The average value of stochastic distribution of 50 replications is considered for the comparison in the case of the simulation approach. A clear identification of variations in the results obtained from the seven performance prediction models are shown in Figure 3.6. The bars correspond to the utilization obtained for same project while the orange line shows the actual value obtained from the site data. Overall, it can be seen that for projects in which open TBMs were used, a variation in utilization of ~30% was observed, while for projects using a double-shielded TBM, up to ~50% variation in estimated machine utilization was recorded (Figure 3.7). The possible reason of variability can be because of a biased data used as a base in formulating the equations for the prediction models. However, RME showed considerably reliable results which had only 1.734 km of data for open TBMs which means that further check of this model is required to ascertain its sensitivity to the TBM types.

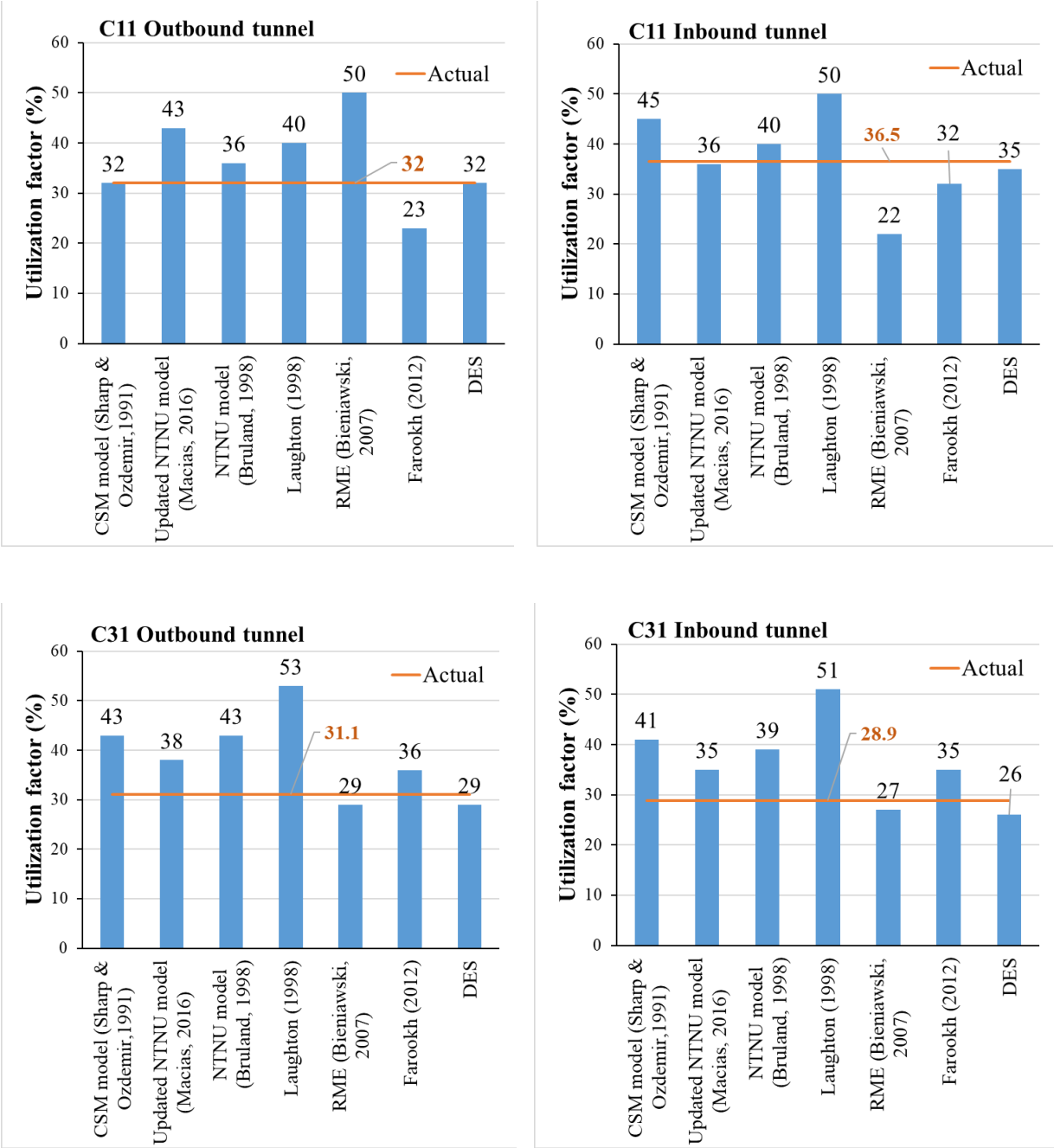
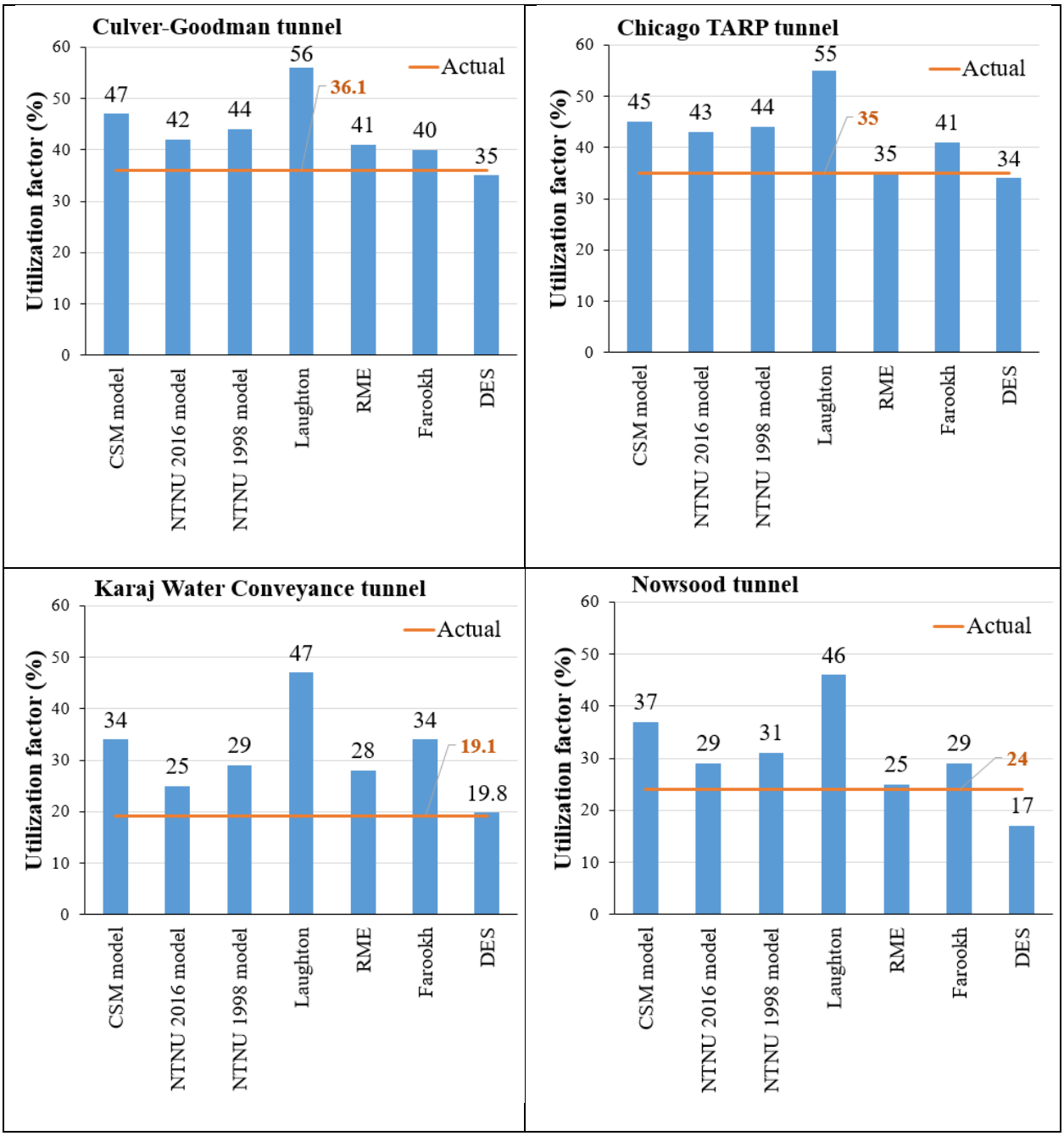


Figure 3.6. Comparison of actual utilization with the predictions from seven performance prediction models for eight projects


Culver-Goodman tunnel
Utilization factor (%)
Actual
36.1
47
42
44
56
41
40
35
CSM model
NTNU 2016 model
NTNU 1998 model
Laughton
RME
Farookh
DES
Chicago TARP tunnel
Utilization factor (%)
Actual
35
45
43
44
55
35
41
34
CSM model
NTNU 2016 model
NTNU 1998 model
Laughton
RME
Farookh
DES
Karaj Water Conveyance tunnel
Utilization factor (%)
Actual
19.1
34
25
29
47
28
34
19.8
CSM model
NTNU 2016 model
NTNU 1998 model
Laughton
RME
Farookh
DES
Nowsood tunnel
Utilization factor (%)
Actual
24
37
29
31
46
25
29
17
CSM model
NTNU 2016 model
NTNU 1998 model
Laughton
RME
Farookh
DES

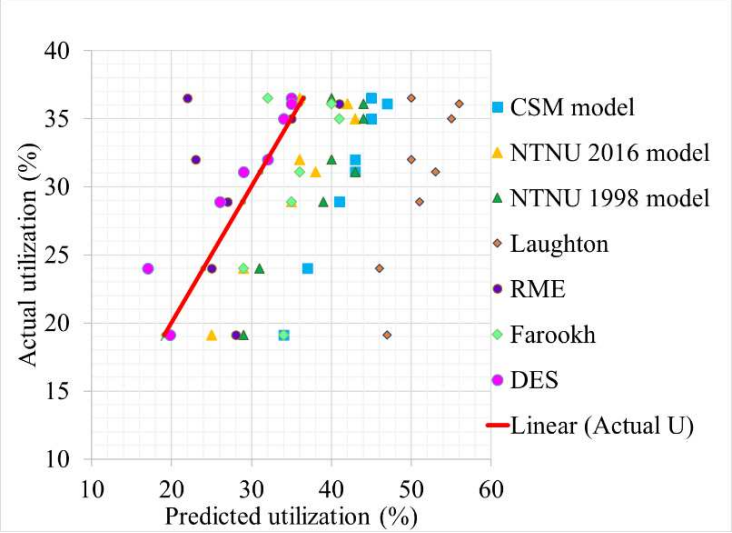


Figure 3.7. Comparison of Utilization estimated by different performance prediction models with actual value for 8 projects.

3.7 Conclusion

Estimation of utilization is very important in accurate estimation of the daily advance rate and completion time of the projects involving TBMs. The current study was performed to determine the sensitivity of selected models for utilization prediction on different projects. Seven different models were considered in addition to DES simulation. The DES simulation showed an average of 7% variation from the recorded machine utilizations in the projects analyzed in this study. This indicates the potential of DES simulation to be a more reliable approach. Furthermore, DES simulation allows for incorporating different tunneling activities in sequence of tunneling that are pertinent to the site conditions, thereby providing for flexibility in the modeling and for including site and machine specific parameters in the related sensitivity analysis and equipment selection.

The other models showed much higher variations. Incorporation of tunnel length in the Macias (2016) model showed considerable improvement in the prediction when compared with

the Bruland (1998) model with variation of 11%. The Farrokh (2012) model showed significant deviation in the utilization estimation for double shield TBMs, suggesting using caution in applying it for projects with these types of TBMs machines. The CSM model overestimated the utilization, so did Laughton (1998) and Frough and Torabi (2013) model, perhaps due to lack of accounting for delays caused by tunnel logistics, and that these models are primarily based on the rock mass behavior. The variability in results in the RME method predictions occur mainly because all the delays due to logistics and maintenance are not considered in the model and estimation of utilization is indirect. The Q_{TBM} was considered but was not included in the comparison as detailed data required as input parameter for indirect estimation of utilization for all the projects was not available.

In summary, this study shows that DES modeling can offer acceptable approach for estimation of TBM utilization. The DES models using Arena© require access to this software which may limit accessibility for other users, and therefore further effort is underway to develop a versatile model that can be made easily available to the tunneling industry for upcoming projects to offer a reliable estimate of machine utilization with the ability to incorporate ground conditions and site set up.

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CHAPTER 4

INTRODUCING UNIFORM DISCRETE EVENT SIMULATION MODEL USING ARENA© SOFTWARE

4.1 Abstract

The components in predicting the TBM performance (advance rate) are rate of penetration and utilization. A few models have been developed to predict machine utilization, and these models are based on statistical analysis of available TBM project databases. Apart from the existing models, use of discrete event simulation (DES) for estimation has also been examined for TBM performance prediction. The sensitivity and accuracy of all these prediction models demonstrate strong influence of geological conditions and site settings. The present study proposes a stochastic simulation model, CSM2020 using Arena© software that encompasses the various tunneling activities that contributes to the utilization estimation.

The CSM2020 model provides for more accurate estimation of machine utilization while offering the flexibility to customize the model on the basis of both equipment selection and the availability of data to incorporate the complex interdependencies of different tunneling activities.

Keywords: TBM, discrete event simulation, excavation, tunnel, utilization

4.2 Introduction and background

The tunneling sector is evolving with the increasing demands in expansion of urban infrastructure, and as a result, there is an urge to have efficient and fast tunneling methods. Tunnel boring machines (TBMs) have proven its capability in tunnel construction since 1950s and have evolved with time. The main factor by which the efficiency of the machine is assessed include the daily advance rate, which is product of penetration rate, and utilization. While there are various

models that can predict the penetration rate with reasonable accuracy, utilization estimation models are limited with shortcomings like models being empirical and based on data that are biased towards certain machine types. The widely used models for utilization estimation are Colorado School of Mines (CSM) model (Sharp and Ozdemir, 1991), Norwegian Technological University (NTNU) model (Macias, 2016), , Q_{TBM} (Barton, 2000), Rock mass Excavability Index (RME) (Bieniawski et al., 2007), empirical models by Laughton (1998) and Farrokh (2012) and simulation based model by Abd-Al Jalil (1998). All these models are based on the database that were available at that time and most of them have not been updated since then. The advantages and disadvantages of these models are presented in Table 4.1. It can be seen that while these models show the capability to encompass some of the critical factors, the uncertainties related to the input are not accounted for that is required to assess the possible best and worst case scenarios. These uncertainties can be those related to capability of crew, ground conditions, muck and supplies transportation system, backup systems, condition of machine, machine configuration like number of motors among others.

Decision Aid in Tunneling (DAT) shows the capability to encompass the uncertainties related to tunnel construction (Einstein, 2002). This method helps in decision making since the beginning of any project like alignment selection, tunnel construction techniques, resource allocation considering the uncertainties related to conditions of the ground thereby providing a distribution of cost versus total construction time. This model is based on discrete event simulation approach where the randomness in the various ground classes, tunnel cross sections, initial and permanent support measures as well as excavation methods were based on Monte Carlo method (Halabe, 1995). The utilization of the resources is one of the factors that is the input in the model and therefore, the utilization of the machine cannot be estimated using this approach.

The stochastic behavior of tunneling operation can be seen in the simulation method, since the tunnel construction is a cycle of activities consisting of events that exhibit a variability in their required time, represented in form of a probability distribution function (PDF). Hence, in order to consider the stochastic behavior of the tunneling operation using TBM for utilization estimation, a different approach need to be formulated. Discrete event simulation (DES) is used in the present study to consider this aspect of tunnel construction.

Table 4.1. Advantages and disadvantages of the different performance prediction models

Model name	Advantages	Dis-advantages
Sharp & Ozdemir (1991)	• Rock mass quality considered in terms of RQD and rock support installation that are related indirectly to RMR value. • The effect of fractures considered in terms of rock support installation. • The effect of groundwater is considered. • The geometry of tunnel is considered. • Labor delays (shift change, safety meeting, lunches) are considered. • Effect of learning curve is considered.	• Based on data available in 1991 and hence do not include the technological advancements. • The empirical formulas are project specific. • Underestimates the downtimes. • Overestimates the utilization. • Do not consider probe drilling, crew's and contractor's experience. • The time allocation for back-up maintenance is not considered. • The effect of torque, cutterhead specifications are not considered. • Constant values for downtimes/delays are considered for the whole tunnel alignment.
Laughton, 1998	• The model tries to optimize the issue from the beginning of the project i.e. from the planning phase. • The model can be logically extended for its use in planning of soft ground and micro-tunneling.	• Combined downtimes of tunneling activities are considered. • The effect of diameter and bored length relates to the rock mass behavior only and is not related to other tunneling activities. • The tunnel logistics are not defined in the utilization factor calculation. • Empirical formula is provided based on the data with low abrasive, dry rocks. • The estimation of U is based only on the rock mass behavior.

Table 4.1 Continued

Abd-Al Jalil, 1998	• Discrete event simulation (DES) is used to predict the utilization factor. • Probability distribution functions (PDFs) are used as input file for the DES model. • Effect of extreme mining areas (in terms of geology) are considered.	• The downtimes are considered altogether in the analysis. • Based on data available at that time. • No definite set of formulas are given for this method. • No clear definition of sequence (tunneling activities in series and parallel) of tunnel activities are provided.
Macias (2016), Bruland (1998, 1998a)	• Based on 26 tunnel projects with 206 km of tunnels. • The effect of tunnel diameter considered indirectly in cutter life calculation. • The effect of tunnel length is considered. • The effect of contractor's skill level is considered. • Effect of learning curve is considered.	• The effect of rock mass condition is not considered. • The effect of tunnel slope, curves are not considered. • The database is of Scandinavian rocks (mostly metamorphic and igneous) reflecting biased analysis. • The time allocation for back-up maintenance is not considered. • The machine specifications are not accounted for in the model. • Constant values for downtimes/delays are provided for the whole tunnel alignment. • The downtimes related to rock support, waiting for transport, tracks and maintenance, surveying, utility extension, washing and cleaning of backup, change of crew, incidental lost time are lumped together as miscellaneous activities for which constant values are specified for given number of tracks in the back-up. • Extra time is considered for the setting up underground assembly chamber, poor rock mass quality, installation of permanent rock support and lining work but no specific formula is provided for it. • Distinction in the machine type is not considered. • TBM cutterhead design is not included as a separate parameter.

Table 4.1 Continued

Q_{TBM}, 2000	• The effect of rock mass (joints, stress condition, strength, quartz content) is considered. • Considers cutter load. • Based on 145 tunnel projects having 1000 km of TBM tunnels. • Considers directly the value of cutter value index (CLI). • Effect of learning curve considered as deceleration gradient reduced by 0.05.	• No direct estimation of utilization factor is provided. • Involves 21 unknown parameters. • Machine logistics are considered in terms of negative gradient. • Tunnel geometry and alignment is not considered. • Estimation of parameters like quartz content, induced biaxial stress involves complex experimental tests and analysis. • Effect of water inflow is not considered. • All the delays related to logistics are combined in a factor called declining or deceleration gradient (m) and hence no specific logistic issue can be considered.
Bieniawski et al., (2007)	• Is based on TBM types in hard rock. • Very simple and easy to calculate. • Effect of learning curve is considered. • Used database for 175 tunnel sections of which 157 were double shield. • Effect of contractor's and crew experience is considered. • Effect of tunnel length and diameter is considered.	• No direct estimation of utilization factor. • Formula for double shield machine is applicable when the machine is working in double shield mode only. • The delays of logistics are not considered. • The logistics and maintenance delays are not considered individually. Therefore, the bottlenecks cannot be identified. • The advance rate (AR) formula for open TBMs are based on 1.724 km of tunnel, for single shield is based on 3.62 km of tunnels and for double shield is based on 20.7 km of tunnel
Farrokh, 2012	• Database of 89 tunnel projects from 20 countries are considered with diameter varying from 2.1 m - 11.52 m and tunnel lengths from 134 m - 17040 m constructed between 1975 and 2009. • The model distinguishes machine type and accounts for cutter change, ground support, water inflow and TBM and backup downtimes.	• The model provides empirical relationships and constant numbers based on case studies. The variability is not considered. • Some parameters are taken from the existing models like the utility extension delay that corresponds to the same in CSM model. • Parallel activities are difficult to consider. • The model does not account for conditions such as extreme water inflow, gassy ground and very soft ground.

4.3 Discrete event simulation

The core of stochastic simulation model is to generate random variables that influence the behavior of the system. Monte-Carlo simulation is a random-number generator having the capability to simulate both probabilistic and deterministic problems (Pegden et al., 1995). DES is defined as a method that can simulate events occurring in sequences thereby presenting its influence on other events. The major advantage of this approach is its capability to encompass variety of events or processes and their complexities and interdependencies and therefore are used widely in simulation of computer network, business process, data implementation, vehicle manufacturing, transportation modes and traffic issues, among other applications (Sharma, 2015). The details regarding the application of DES in tunneling and other industries are discussed in earlier chapters.

4.4 Simulation methodology

The objective of this study is to prepare a DES based model that develop a stochastic distribution of machine utilization. Figure 4.1 shows the flowchart of the simulation model prepared in Arena© simulation software. The flowchart shows the activities when shift starts. These activities are in the form of modules in the simulation model. The simulation model is named as CSM2020 model. It can be seen from the chart that first a regular meeting is held wherein the previous crew updates the progress made to the next crew after which the crew goes to the TBM to start the construction process. It starts with regular check of equipment, cutterhead, conveyor belts etc. after which the requirement of probe drilling is checked. The utility extension is also checked before excavation. If the muck transportation is via muck cars, then excavation process is only started once the car is available at the backup area. If conveyor system is used for muck transportation, then excavation process is immediately started. In projects where segment

installation is required, this activity is also performed which can be a parallel activity in case of double shield machine working under good ground. However, in fault zone areas, the double shield machine works in single shield mode and segment installation is then in series with boring. If the machine is open type, support measures are required based on the ground condition. The simulation model checks the various activities that can occur at the back up area, which are in series with boring, and directly affect the utilization estimation. These include electrical, mechanical, hydraulic delays, maintenance work and others. The transportation related activities are also accounted for in the simulation model wherein the activation of California switches with increasing tunnel length are also incorporated. Delays like track replacement and repair, derailment, unloading and loading of supplies, muck dumping, wait at the California switch are also considered in the model. Unexpected breakdowns like cutterhead not rotating, sudden collapse of electrical system, unexpected ground conditions are lumped as one module in the CSM2020 model. The surveying using total station or similar occurs at certain intervals usually at end of shift and is therefore in series with the boring process. Finally, the model checks whether the shift is over or next cycle is to start and the process continues (Figure 4.2, Figure 4.3, and Figure 4.4). Table 4.2. shows the list of activities that are in series or parallel with boring process. In CSM2020 simulation model, the activities that can either be in series or parallel with boring, or parallel with each other and are modelled as parallel events. For example, for activities such as segment installation, the model first checks the type of TBM (open, single or double shield) and then makes the decision accordingly.

Table 4.2. List of tunneling activities considered in CSM2020 model

Parameters	Activities	Series / parallel with boring process
Excavation	Boring	-
Ground troubleshooting	Rock bolts installation	Series / parallel
	Wire mesh installation	Series / parallel
	Grouting	Series
	Rockfall clear at invert	Series / parallel
	Clean cutterhead	Series
	Cutter inspection	Series
	Cutter change	Series
	Segment installation	Series / parallel
	Water proofing membrane installation	Series / parallel
	Regrip	Series
	Probe drilling	Series
	Shotcrete	Series
	Other ground troubleshooting	Series / parallel
Maintenance	Routine maintenance	Series
	Regular Clean TBM	Series
Utilities	Mechanical	Series
	Electrical	Series
	Hydraulic	Series
	Water pipe	Series
	Ventilation cassette installation	Series
	Power cable stacking	Series
Transportation	Waiting for train	Series
	Derailment delays	Series
	Train pass delays	Series
	Track placement and repair	Series
	Muck dumping	Series
	Supplies delay	Series
Survey	Surveying delay	Series
Miscellaneous	Shift change	Series
	Safety meeting / daily progress meeting	Series
	Lunch break	Series
Unexpected breakdown	Other Unexpected delays	Series
	Failure of equipment	Series
Crew	Effect of crew	-

The formula for utilization estimation is

$$Utilization\ (U\%)\ = \frac{\mathrm{T}_b}{\mathrm{T}_b + \mathrm{T}_g + T_m + T_u + T_t + T_s + T_{ub} + T_{me} + T_o + \cdots.} \times\ 100$$

Where T_b is the boring / excavation time, T_g is the ground related delays, T_m is the maintenance related delays, T_u is the time taken to extend utilities, T_t is the transportation related delays, T_s is the surveying time, T_{ub} is the time to repair the unforeseen breakdown, T_{me} is the combined meeting, lunch, shift change time and T_o is the other activity times.

The U is estimated after each stroke and the process are repeated for the whole length of the tunnel taking into account the effect of distance of TBM face from portal. This cycle is replicated number of times to obtain the stochastic behavior of the model. The number of replications can vary depending on the requirement of the user. However, an optimum replication number of 50 was found to be enough, when analyzing the error between the actual and predicted values as given in Khetwal et al. (2020).

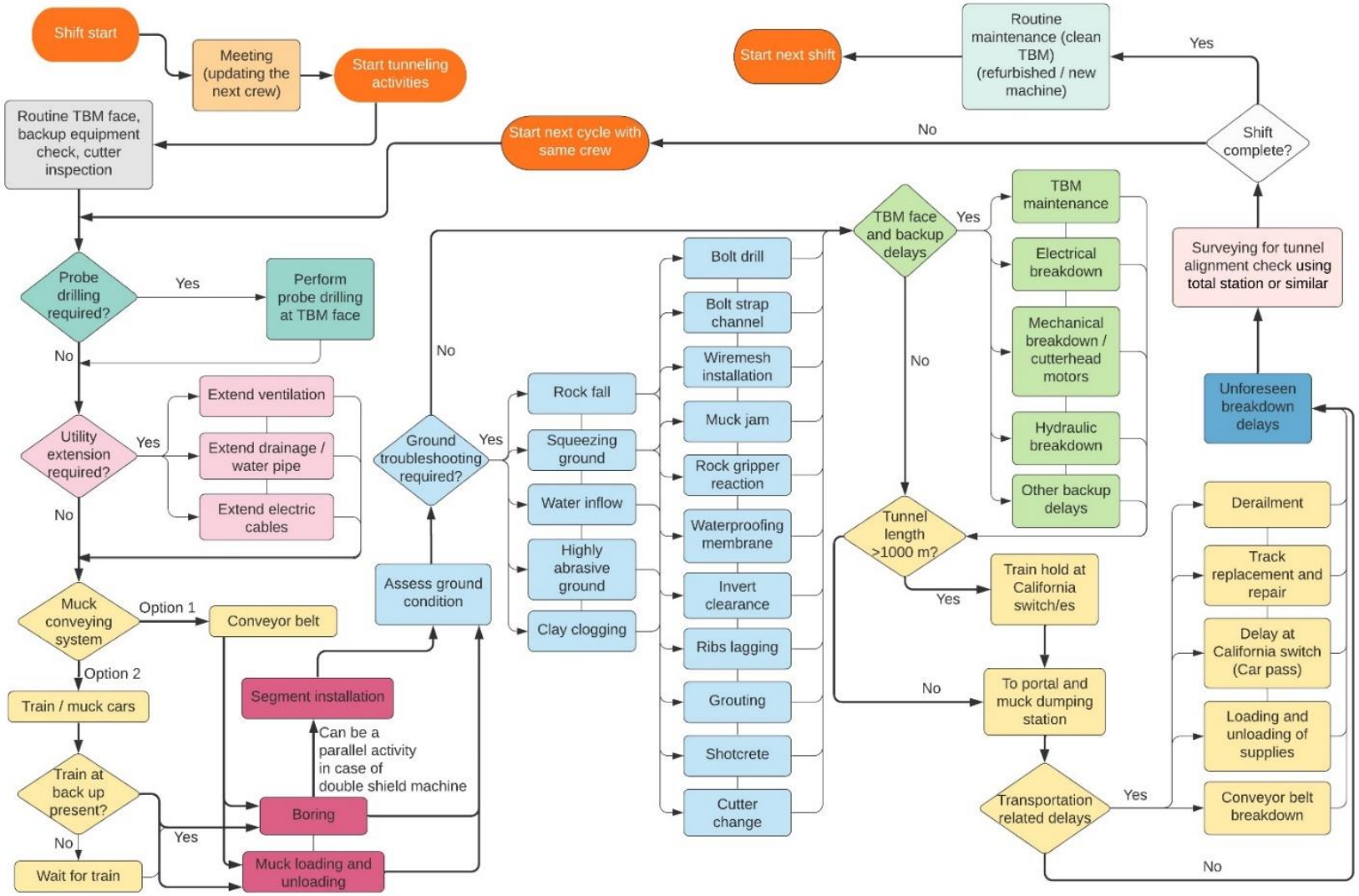


Figure 4.1. Flowchart showing the tunneling activities considered in CSM2020 model for U estimation

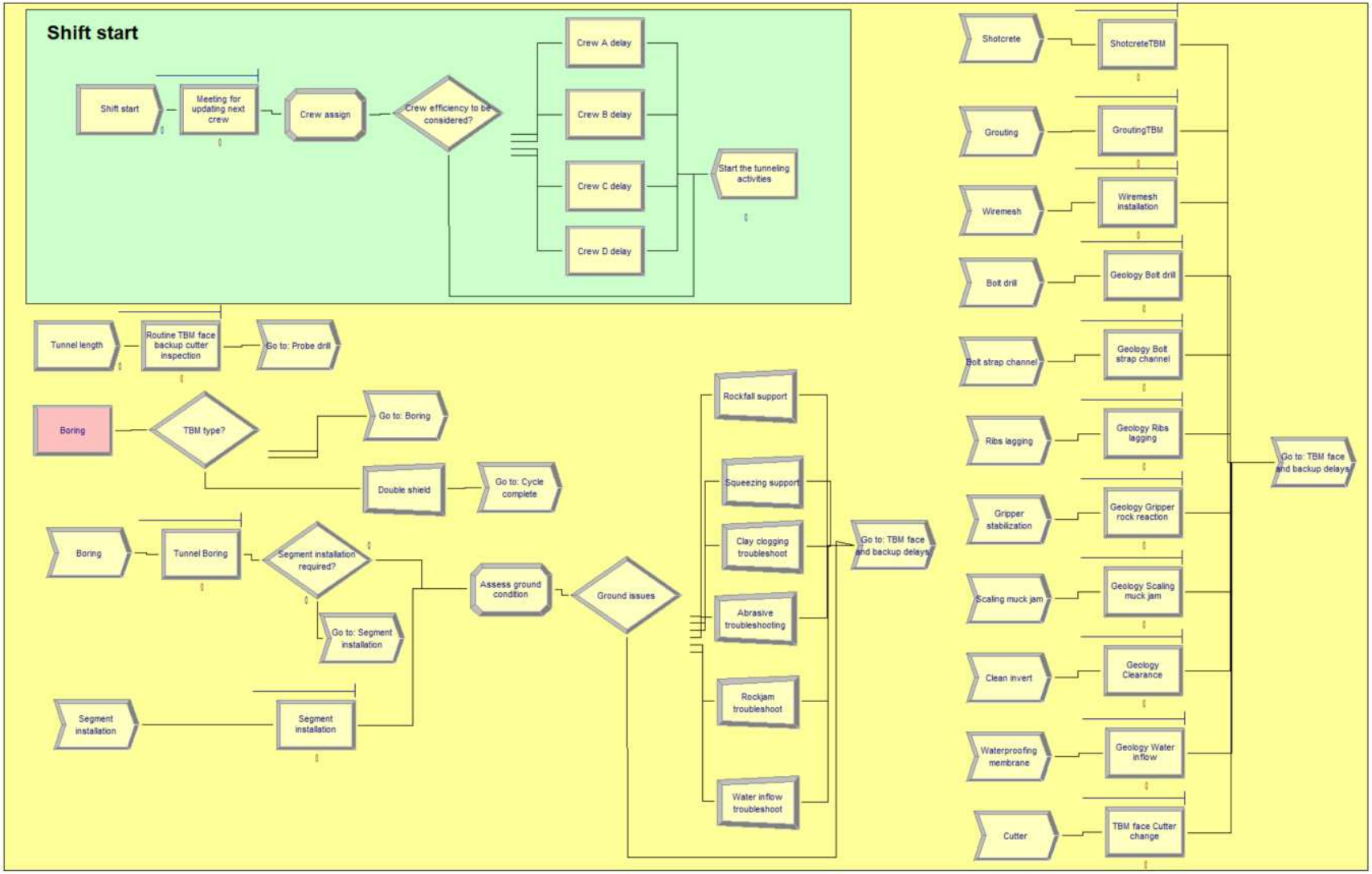


Figure 4.2. CSM2020 – Arena© simulation model – part 1

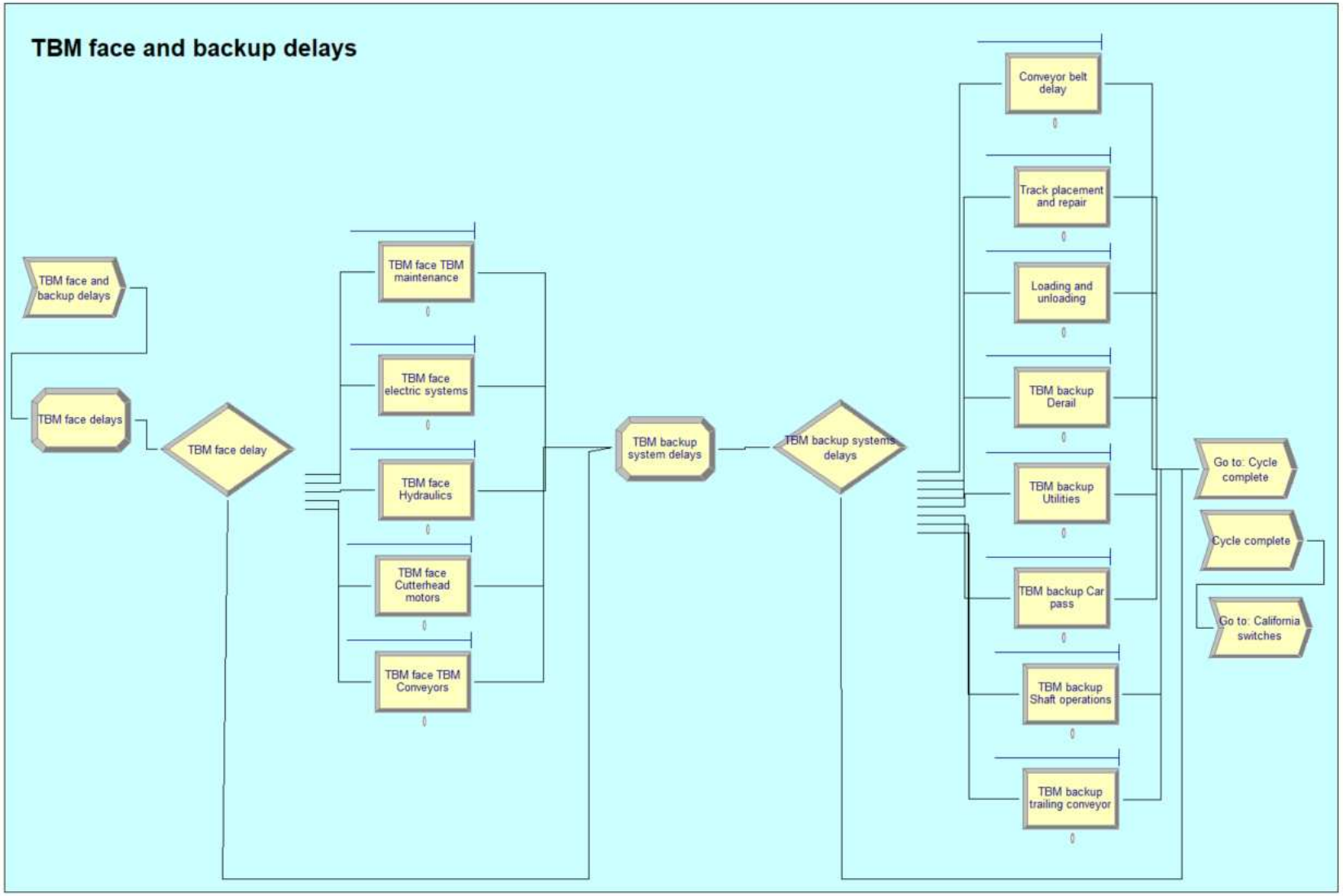


Figure 4.3. CSM2020 – Arena© simulation model – part 2

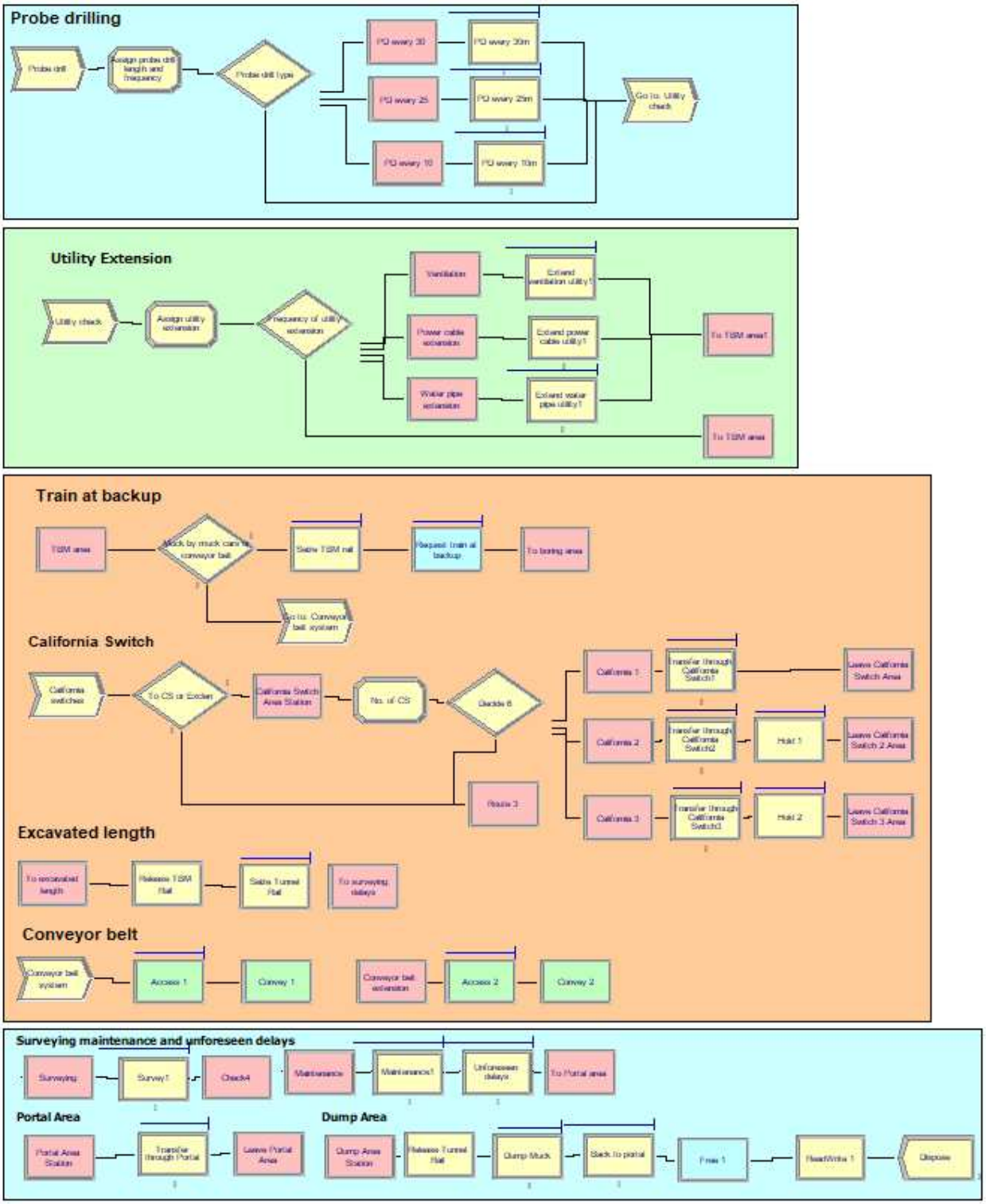


Figure 4.4. CSM2020 – Arena© simulation model – part 3

4.4.1 Meeting module

The meetings are generally performed when the shift ends as the previous crew provides a brief summary of the work to be done and the issues they came across during the earlier shift. This meeting helps in smooth transition of the job from one crew to another with a combined decision regarding the troubleshooting measures to be taken for the efficient tunnel construction. The time taken by the crew to have lunch and small breaks are also included in this module. Since the crew are not involved in any tunneling work at this time, this activity is in series with boring. The data from the three projects offered a lognormal distribution fit with the p- value of 0.846 and mean of 1.4 hour per shift as shown in Figure 4.5. The 'Seize Delay Release" action means first an entity is seized as the given number of resources, then it is delayed as per the service time given and finally released so that other modules can seize it.

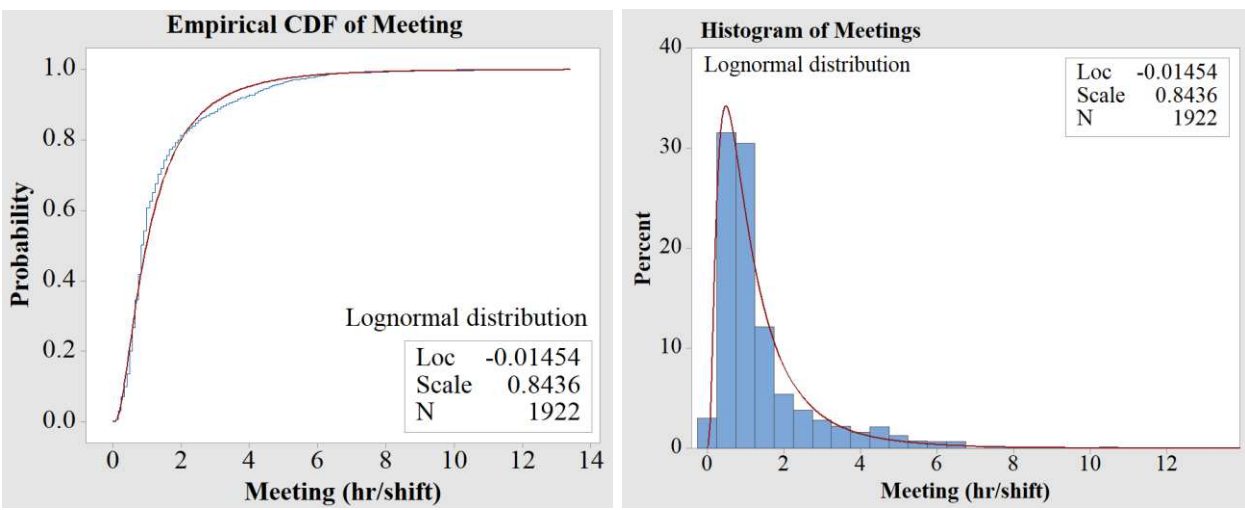


Figure 4.5. Empirical CDF, PDF for meeting time

4.4.2 Crew efficiency

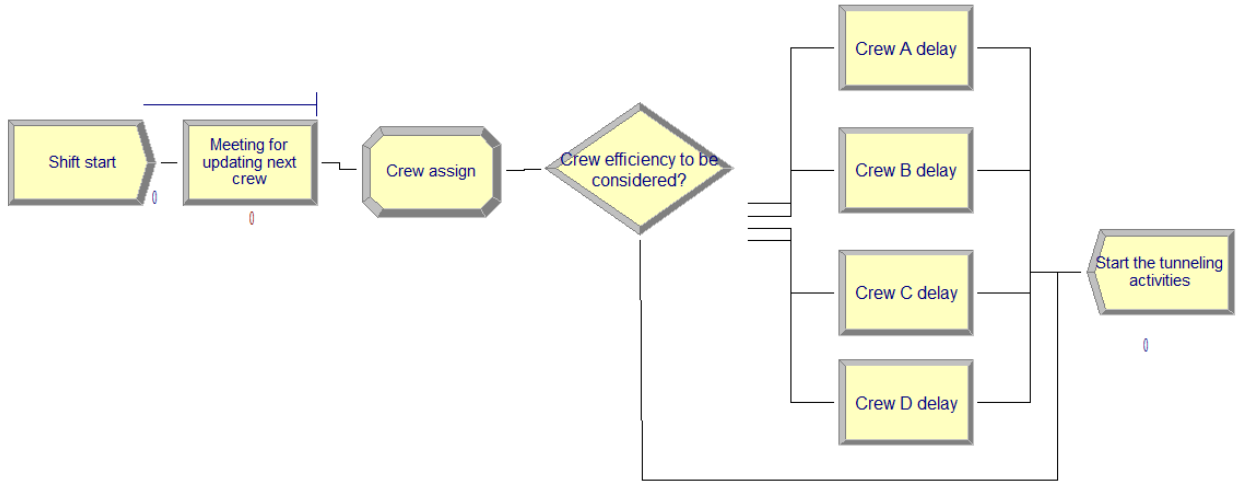


Figure 4.6. Crew efficiency input module in CSM2020 model

The crew efficiency in the model was incorporated as an overall delay per shift that account for delays in management of tunneling activities as shown in Figure 4.6

The analysis of the mean values of the data of four crews as obtained from the Stillwater mine project as shown in Figure 4.7 and it can be seen that Crew B takes maximum time to perform a task. However, after conducting interview with the manager, Crew B was most experienced and efficient. The greater number of hours is attributed to more machine repair tasks being assigned to them that can only be handled by experienced crew. Hence, this data was not used in the simulation model. The variation due to crew efficiency is given in Table 4.3.

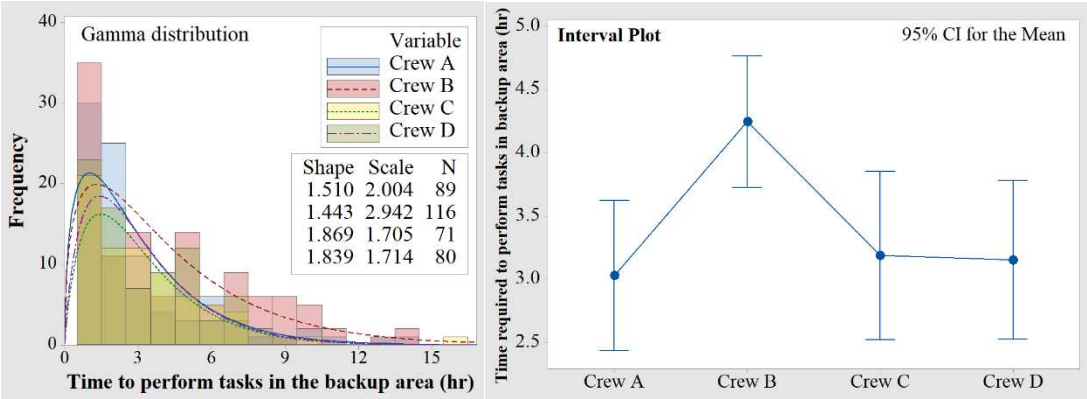


Figure 4.7.. Task performed by different crews per shift

Table 4.3. Delays due to crew's efficiency

Factor	N	Mean (hour)	Standard Deviation (σ)	95% CI	Delays in DES simulation model (min)
Crew A	89	3.026	2.855	(2.432, 3.621)	TRIA (0,10,20)
Crew B	116	4.246	3.359	(3.725, 4.766)	TRIA (0,20,30)
Crew C	71	3.185	2.562	(2.520, 3.851)	TRIA (10,20,30)
Crew D	80	3.152	2.207	(2.525, 3.778)	TRIA (15,30,45)

4.4.3 Probe drilling

The probe drilling is required to assess the ground condition ahead of face. In most of the open TBMs, continuous probe drill is performed whose frequency is dependent on the max depth and amount of overlap. Typical probe drilling machine at the backup area is shown in Figure 4.8. The analysis by Khetwal et al. (2020) showed the sensitivity of the utilization towards probe drilling time was rather low, as it registered +/-2% in final utilization, and however it is added as a module in CSM2020 model. Three options of the drill with 10 m, 25 m and 30 m drilling length was added to the model (Figure 4.9). The probe drilling data was available for Stillwater mine project where

25 m length was used. However, continuous probe drilling was not used in Stillwater project and the decision was taken by the TBM manager on the basis of the ground condition. Yet, since no other data was available, this was used for estimating its time allocation. A Gamma distribution with mean of 4.8 hours is set as input to the model (Figure 4.10). Comparing the actual data with the distribution, the p-value came to 0.92.

Figure 4.8. Probe drilling at Stillwater mine project

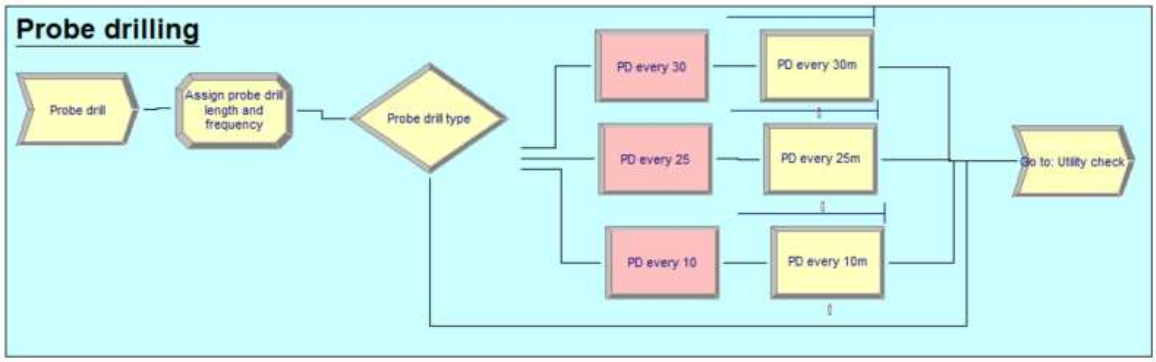


Figure 4.9. Probe drilling module in CSM2020 model

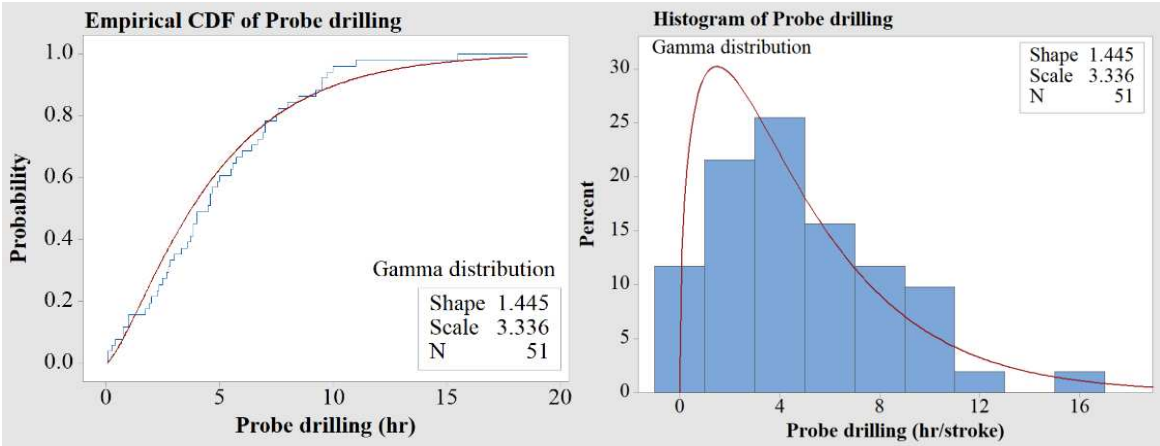


Figure 4.10. Time required to perform probe drilling with 10 m rod

4.4.4 Utility extension

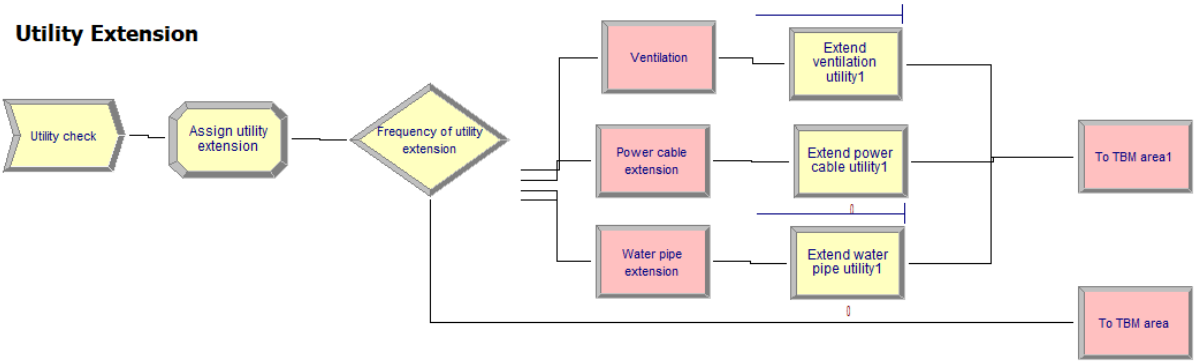


Figure 4.11. Utility extension module in CSM2020 model

The requirement of utility extension was checked in each stroke. The three utilities considered are the ventilation ducts, power cables and water pipes (Figure 4.11). These are extended from the TBM backup area to portal / shaft location as the excavation moves forward. The two items that need to be set are the frequency and time required for their installation or connection with the previous pipes. The ventilation cassette is placed at the backup area and after advancing a certain interval, it is connected with the installed duct (200 m in present simulation

model). The power cable similarly is extended every 300 m and water pipe every 100 m. The connection of the cable is either using connector as shown in Figure 4.12 or by infusing them using heat treatment. In the present study, lognormal distribution (Figure 4.13) is used to represent the time allocated to extend utility having mean of 2.3 hours.

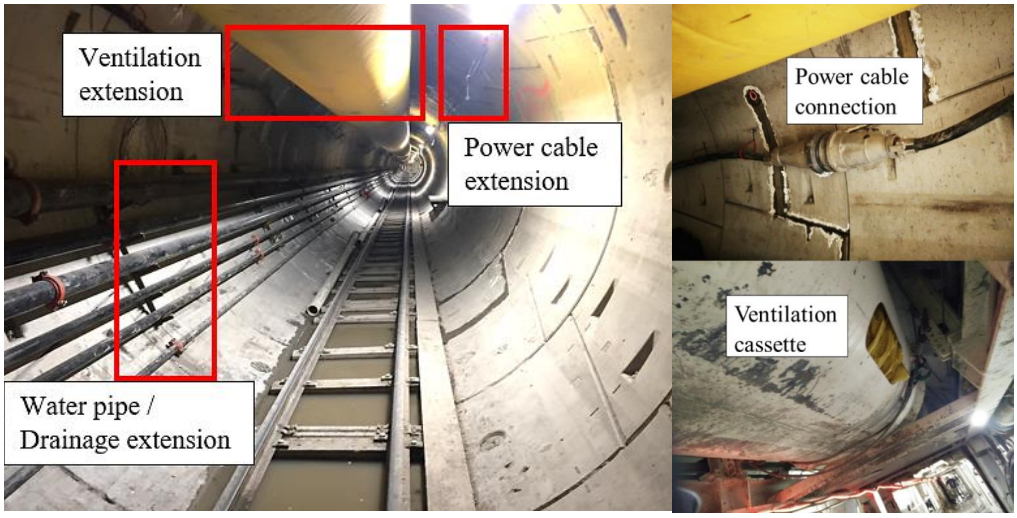


Figure 4.12. Types of utility extensions

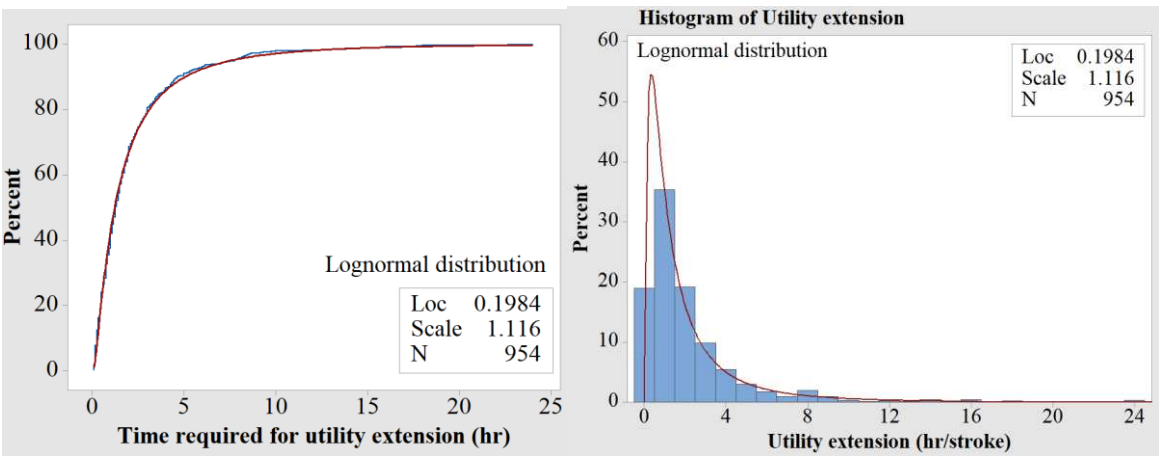


Figure 4.13. Utility extensions time

4.4.5 Transportation and California switches

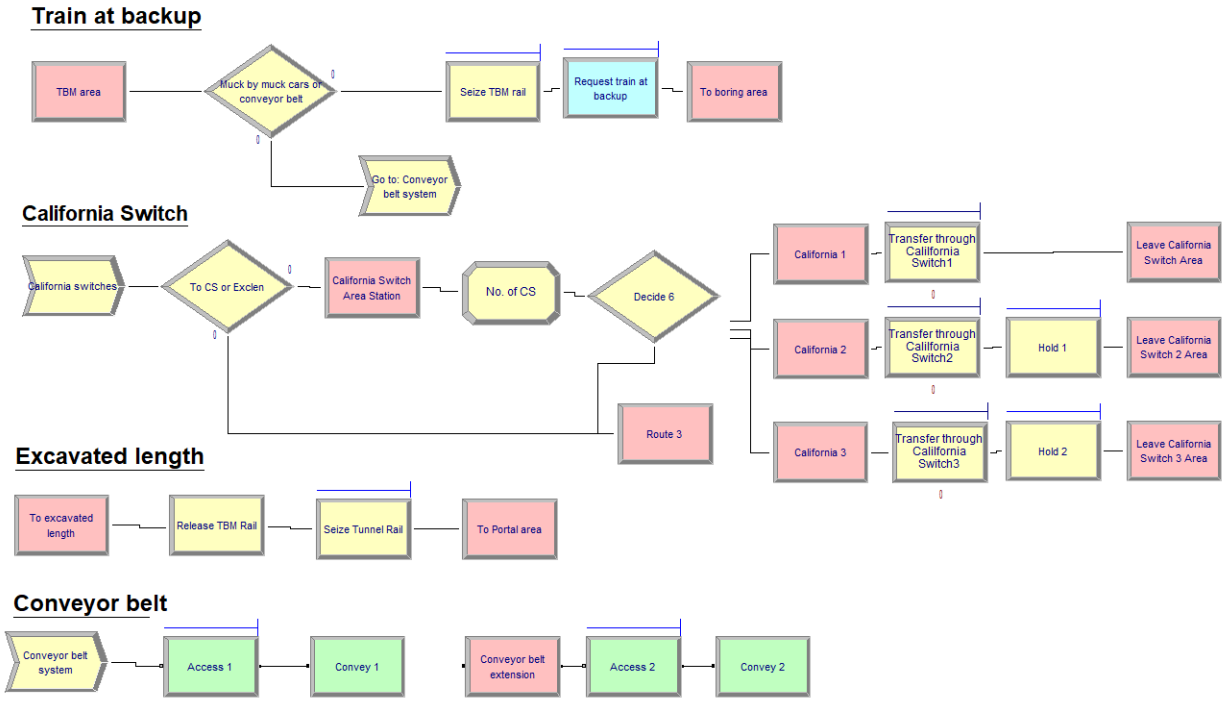


Figure 4.14. Transportation modules in CSM2020 model

The transportation of muck in simulation model can be either by conveyor belt or train as shown under sub-heading "Train at backup" in Figure 4.14. However, the transportation of supplies is however simulated using train only. The simulation model also allows to have multiple trains for supplies and muck transport which can pass each other at the California switches. A typical California switch and rail inside a tunnel is shown in Figure 4.15. The California switches are assigned as the length of tunnel increases. The data regarding activation of California switches were available only for one project and therefore is added to the model. The excavated length corresponds to the initial 1000 m of length of tunnel after which California switch is installed. Second switch is installed at 3000 m and third at 7000 m. At present only three switches are modelled. More numbers of switches can be added as per requirement of the project. The muck

transportation using conveyor belt is simulated with just three modules as shown in Figure 4.14 under sub-heading “Conveyor belt”. Here, the start and end of the belt is given starting from TBM backup area to place where extension of belt is done to portal and finally to dumping area.

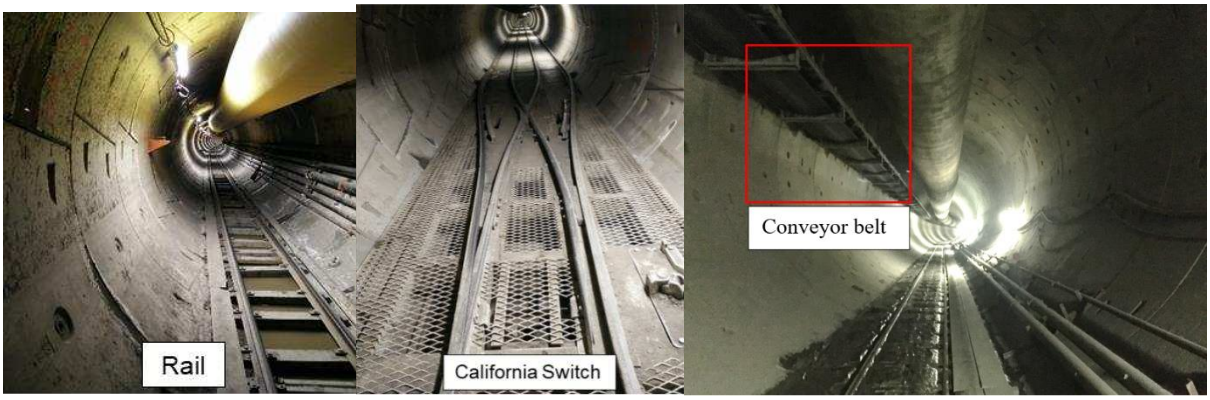


Figure 4.15. Muck and supplies transportation system

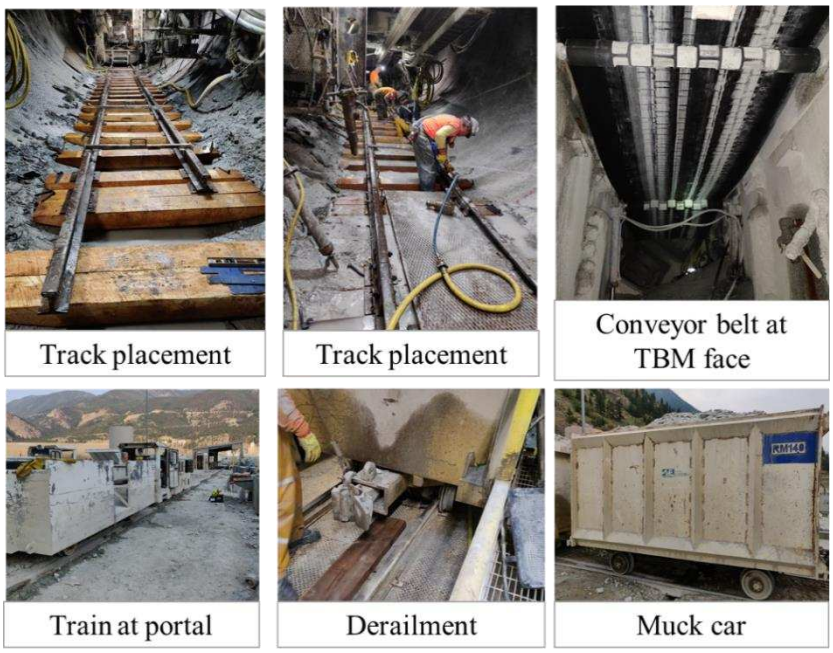


Figure 4.16. Transportation delays

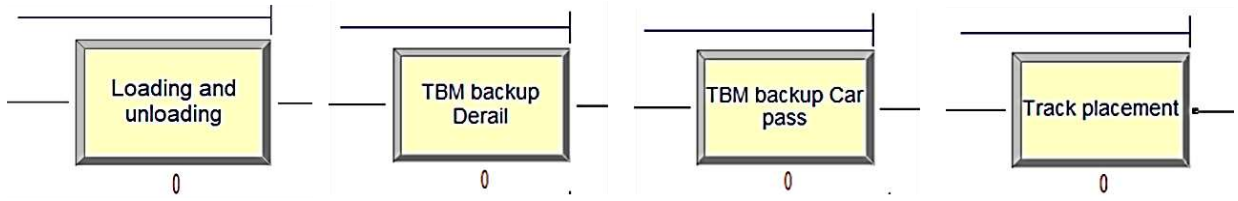


Figure 4.17. Transportation delays modules in CSM2020 model

For simulation of the train, speed of train was given as 15 km /hour. This value was obtained from Stillwater mine project. The model checks whether the train is available at the backup area and then starts excavation. After excavation, the train carries the muck to the dumping area and then returns to the backup area. With the increase in length, the number of trains also increases. When 2 trains are working, then the first train reaches the backup area while the second train waits at the California switch. In this way, the time required for the train to reach the backup area to start the excavation process is minimized. However, when the muck transportation system is via conveyor belt, this issue is not relevant, and trains are used only for transporting supplies from the portal area to the TBM backup area. The delay due to transportation system includes transportation loading and unloading, derailment, track placement and train exchange or car pass (Figure 4.16). These are included as modules under TBM backup area delays (Figure 4.17). The train unloading and loading system delays occurred 109 times for Karaj project, 411 times in Nowsood project and 536 times in Stillwater mine project. Estimating the weighted average, the chance of delay is 3.7 % per unit length. Similarly, derailments occurred 155 times in Stillwater mine project and 133 times in Karaj project and hence the probability of occurrence is 1.03% per unit length. Train bypass delay occurred 742 times in Karaj project and 386 times in Nowsood project. There was no California switch for the Stillwater mine project as it had various stops that were used for the train to pass and hence no data regarding this delay was obtained. The probability

of bypass occurrence is 2.6% per unit length. Delay due to track placement and repair occurred 56 times in Karaj project, 411 and 371 times in Nowsood and Stillwater mine project respectively. Hence, the probability of occurrence of track placement delay is 2.9%. The conveyor problems include the problems that occur at the TBM face and conveyor belt. The division of data for the conveyor belt at the TBM face and at TBM backup area was not available and therefore combined delay is considered in the simulation model. This delay occurred 405 and 438 times for Karaj and Nowsood project. No data regarding this was available for Stillwater mine project. The probability of occurrence for this delay was assigned to be 1.9%.

Table 4.4. Delays due to transportation

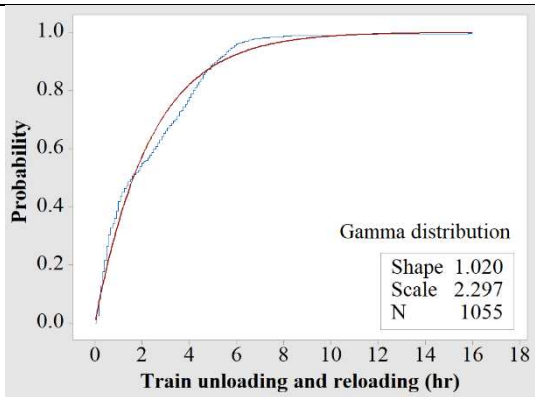
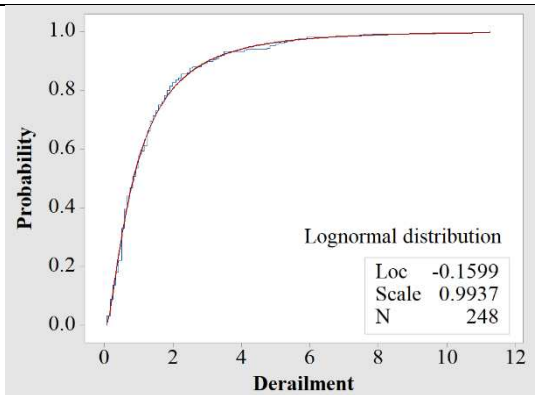
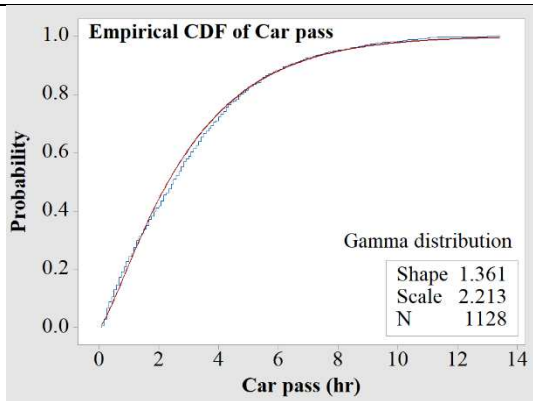
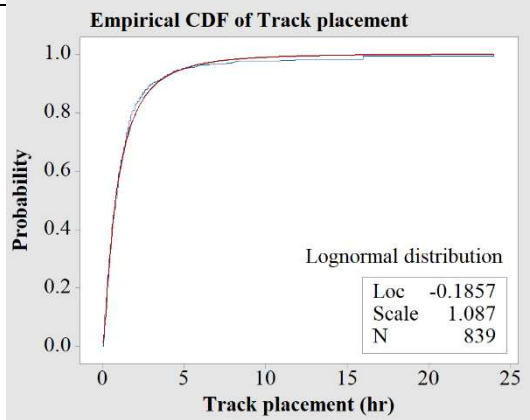
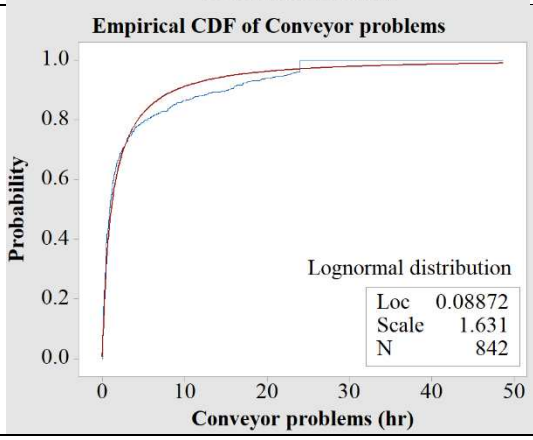
	Empirical CDF	Distribution (in hour)	Probability of occurrence
Train unloading and loading		Gamma (3.24,2.32) (p-value 0.421)	3.7%
Derailment		Lognormal (1.39,1.75) (p-value 0.585)	1.03%

Table 4.4 Continued

	Empirical CDF	Distribution (in hour)	Probability of occurrence
Car pass (at California switch or portal location)		Gamma (3.01, 2.58) (p-value 0.840)	2.6%
Track placement and repair		Lognormal (1.5, 2.5) (p-value 0.235)	2.9%
Conveyor problems		Lognormal (4.1, 15.1) (p-value 0.500)	1.9%

The time distribution of these delays was made from the available data as described earlier. The various distributions were checked and Anderson-Darling (AD) test for goodness of fit was

performed as shown in **Table 4.4.**. The null hypothesis was checked by calculating the p-values and those with more than 5% significance level were true while others were rejected.

4.4.6 Surveying

The surveying module comprises of the time required to carry out surveying using total station to check the alignment and the time taken to change the surveying stations as the excavation proceeds. During this activity, boring is stopped and therefore is considered in series with boring process. The probability of occurrence of surveying related downtime is 1.2 %. The analysis showed that the best fit is Lognormal distribution having mean of 1.9 hours with a p-value of 0.715 (Figure 4.18).

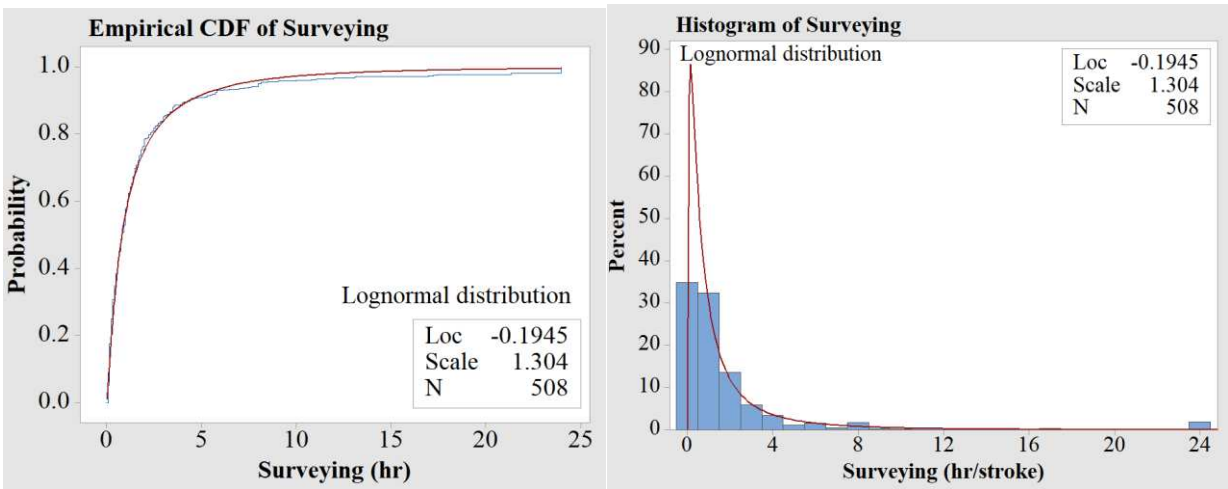


Figure 4.18. Time taken to perform surveying

4.4.7 Cutter change

This module comprises of the time required to change the cutters. In order to determine the frequency and time required to perform cutter change, the data for Karaj, Nowsood and Stillwater mine project were considered. The probability of occurrence came to be 3.1% while the best-fit came to be Gamma distribution (0.8533, 2.950) with a p-value of 0.747 (Figure 4.19).

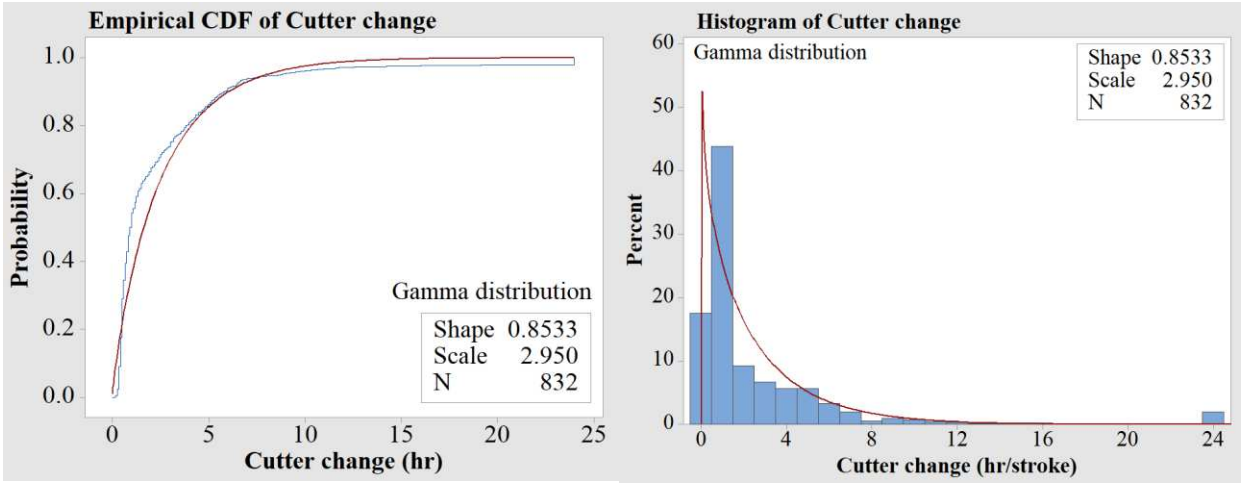


Figure 4.19. Time taken to change the cutters

4.4.8 Ground troubleshooting

This module includes the measures taken to stabilize the adverse ground. It includes installing wire mesh, bolts, straps, shotcrete, waterproofing membrane (water inflow), grouting, ribs lagging, muck jam and cleaning invert (clearance) (Figure 4.20). The delays due to these activities are given in **Table 4.5.** .

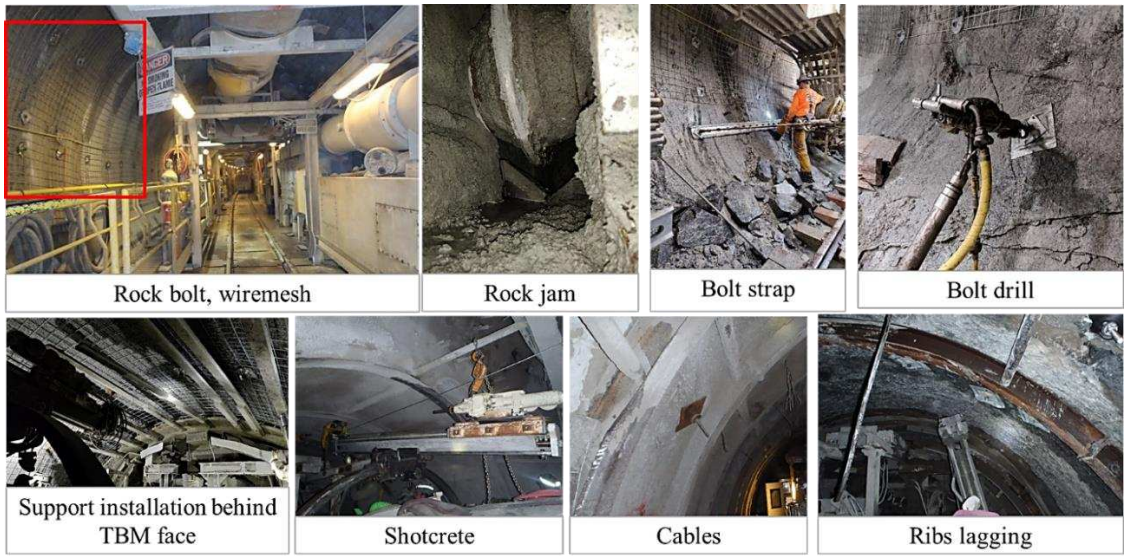


Figure 4.20. Various ground support installations

Table 4.5. Delays due to ground related issues

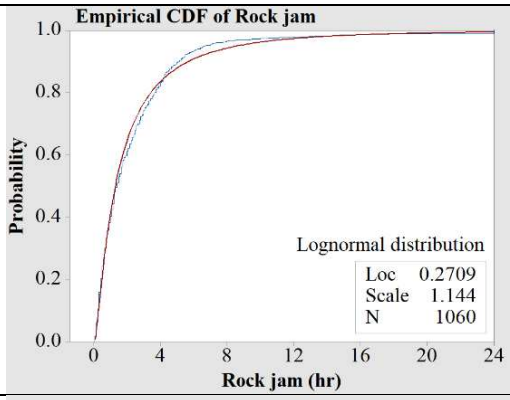
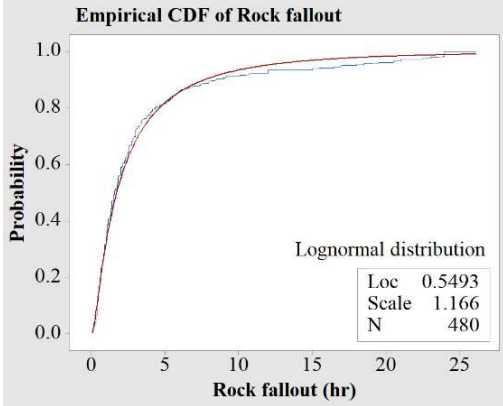
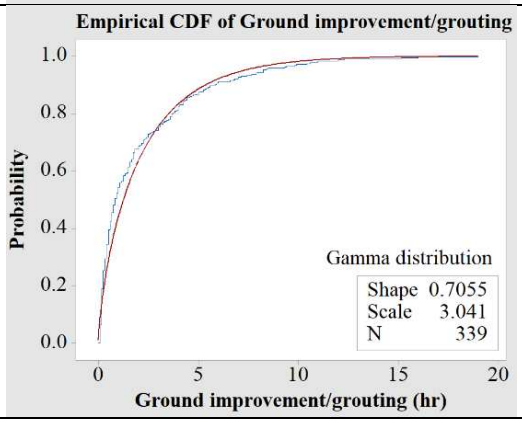
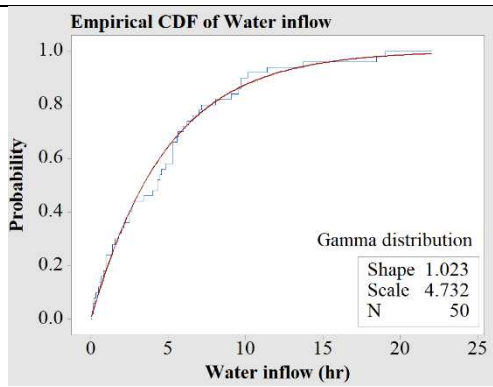
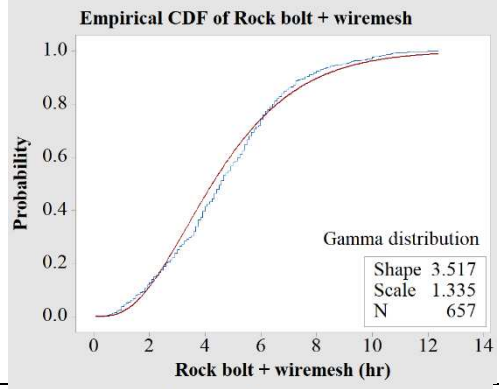
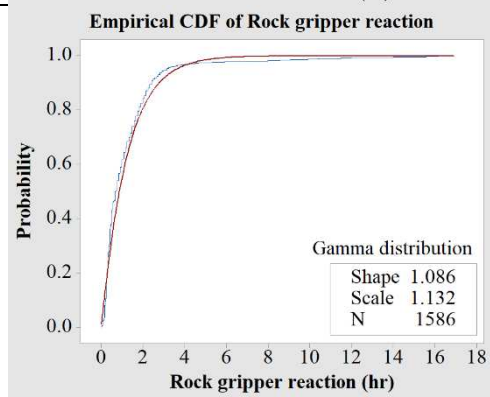
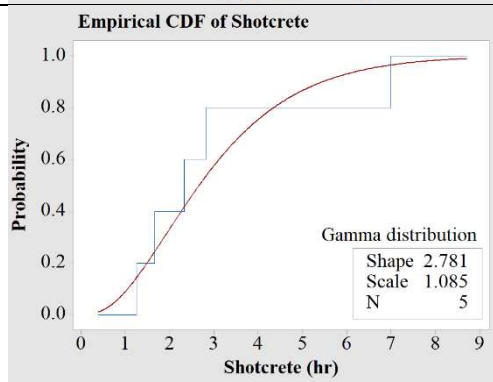
	Empirical CDF	Distribution (in hour)	Probability of occurrence
Rock jam		Lognormal (0.2709,1.144) (p-value 0.817)	2.9%
Rock fallout		Lognormal (0.5493, 1.166) (p-value 0.467)	2.0%
Ground improvement / grouting		Gamma (0.7055, 3.041) (p-value 0.220)	0.8%

Table 4.5 Continued

	Empirical CDF	Distribution (in hour)	Probability of occurrence
Water inflow		Gamma (1.023, 4.732) (p-value 0.545)	0.1%
Rock bolt + wiremesh		Gamma (3.517, 1.335) (p-value 0.348)	3.1%
Rock gripper reaction		Gamma (1.086, 1.132) (p-value 0.667)	2.51%
Shotcrete		Gamma (2.781, 1.085) (p-value 0.432)	0.02%

4.4.9 Electrical

The electrical breakdowns in tunneling operation is related to breakdown due to short-circuit or wire break, transformer breakdown or similar issues. The repair due to this breakdown is in series with boring operation and therefore directly affects the utilization estimation. After analyzing the data from the three projects (KWCT, Nowsood and Stillwater mine), it was found that the frequency of occurrence of this breakdown is 2.65% having a lognormal time distribution having mean of 1.9 hours with p-value of 0.242 (Figure 4.21).

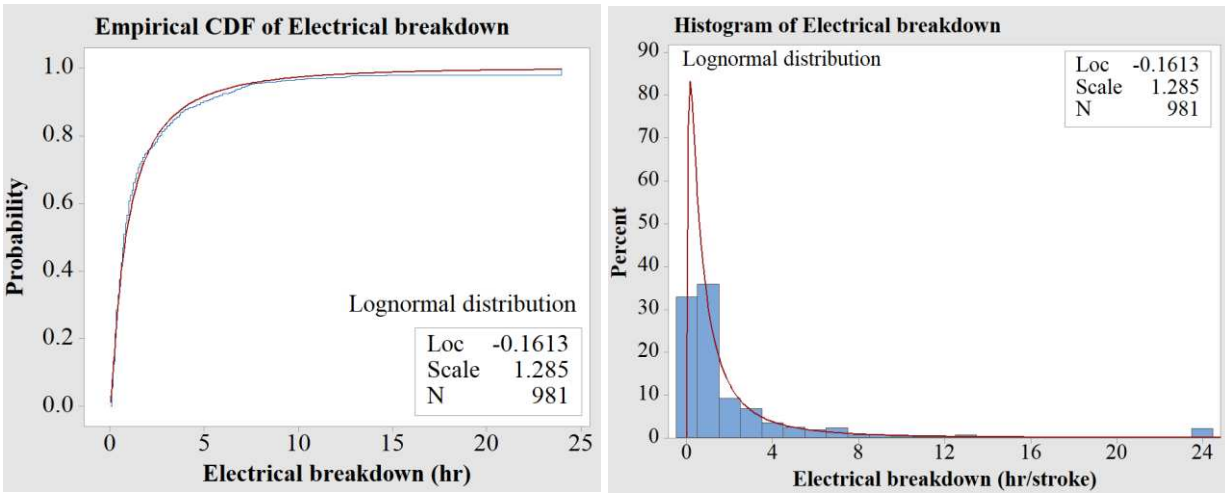


Figure 4.21. Time taken to repair electric breakdowns

4.4.10 Mechanical Breakdowns or Repairs

The mechanical breakdown includes the non-functional hydraulic pumps, motors and other equipment. Boring cannot continue while repairing this equipment and therefore this breakdown is considered in series with boring process. After taking the weighted average of its frequency of occurrence from the three projects, the value came to be 2.67%. The time to repair is gamma distribution with p-value of 0.853 (Figure 4.22).

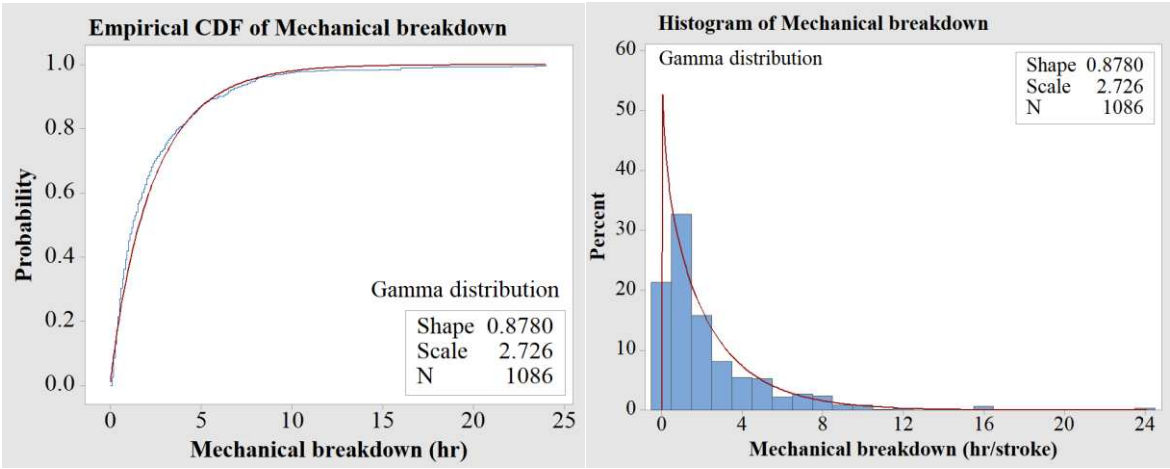


Figure 4.22. Time taken to repair mechanical breakdowns

4.4.11 Hydraulic Subsystem Delays

The hydraulic breakdown includes the non-functional hydraulic cylinders that are required to push to the cutterhead. This repair is also in series with boring having frequency of occurrence of 0.93% as obtained from the analysis of available data from the 3 projects. The time allocated to perform this activity is a lognormal distribution having mean of 2.5 hours as shown in Figure 4.23 with a p-value of 0.683.

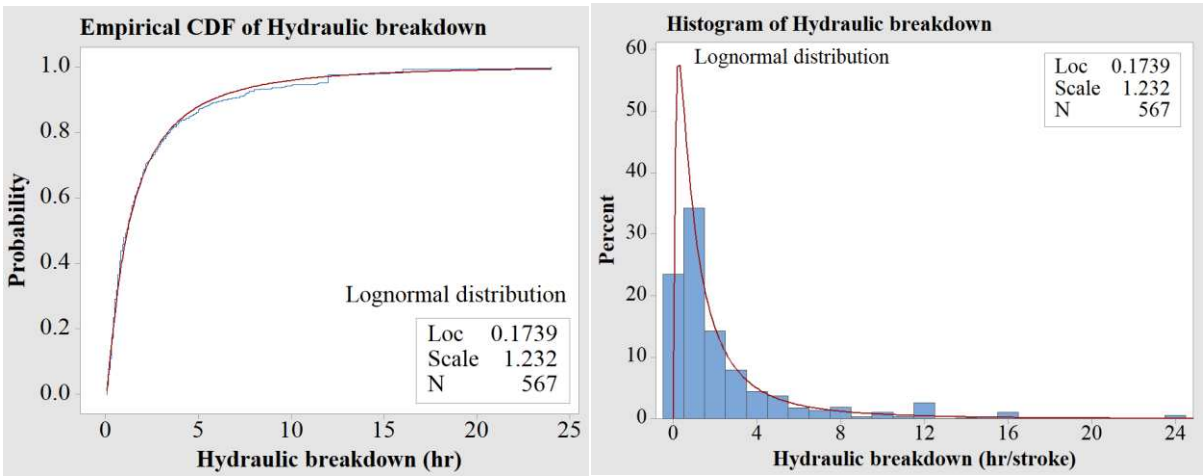


Figure 4.23. Time taken to repair hydraulic breakdowns

4.4.12 Segment installation

In double shield machine, the segment installation is done parallel to boring process and is considered in the simulation model. The double shield machine was used in Karaj and Nowsood project while Stillwater mines had open machine where segment installation was not required. However, only for some length of tunnel, the machine worked in the double shield mode which can be seen by counting the frequency at which this activity was performed. It can be seen that out of a total of 1016 days, this activity was performed for only 863 days while for Nowsood project, it was for 684 days out of a total of 858 days. Therefore, analyzing data from 2 projects, the probability of occurrence came to be 82.3%. The time taken to perform this activity showed gamma distribution with p-value of 0.829 (Figure 4.24).

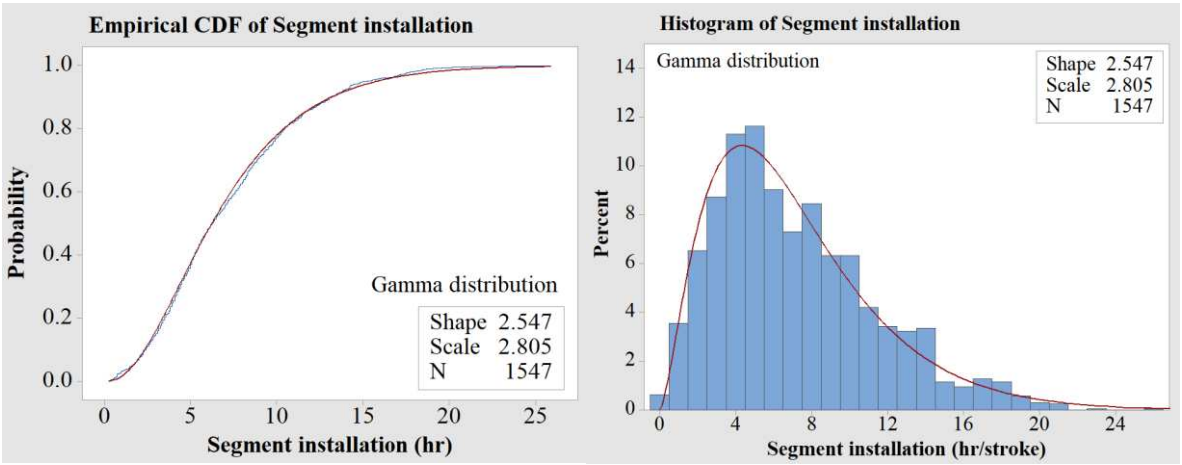


Figure 4.24. Time taken to install segment per stroke

4.4.13 Routine maintenance

The site visits in February 2018 at Blacklick project at Columbus, Ohio had every routine maintenance of 4 hours every day. They had 2 shifts of 10 hours each and rest 4 hours was for routine maintenance. By analyzing the data of Karaj, Nowsood and Stillwater mine project, it was

seen that maintenance delay was 212 days out of total of 1019 days for Karaj project while for Nowsood, it was 236 days out of 858 days and only 3 days out of 735 days for Stillwater mine project. The graphs in Figure 4.25 shows the maintenance delay and maintenance activity both having a gamma distribution with p-value of 0.434 and 0.719 respectively.

The condition of the machine being new or refurbished also affects the overall performance of the machine. Macias (2016) mentioned the time required for setting up refurbished and new machine are 3 to 6 and 6 to 1 year respectively. However, the assembly and disassembly of the machine at the project site usually takes around 4-8 weeks that also depends on the TBM diameter.

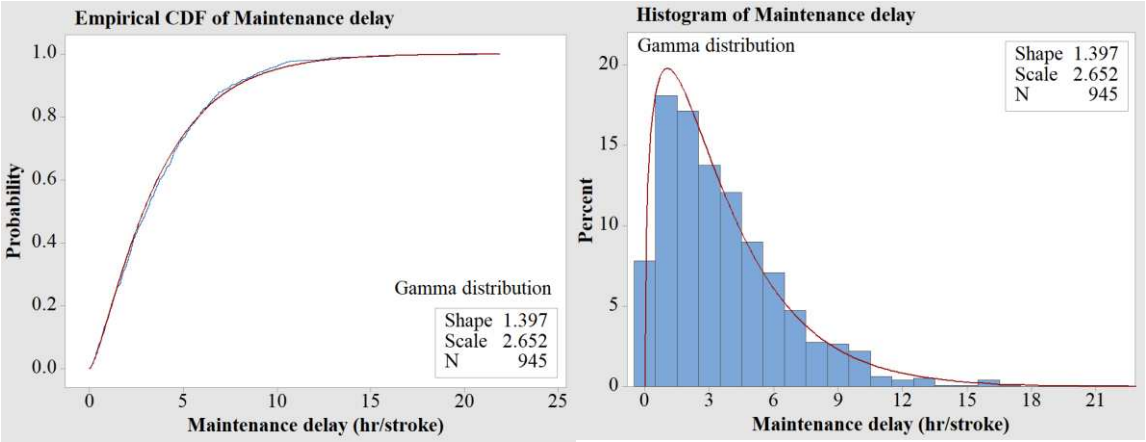


Figure 4.25. Time allocated for delays in maintenance

4.4.14 Portal and muck dumping area

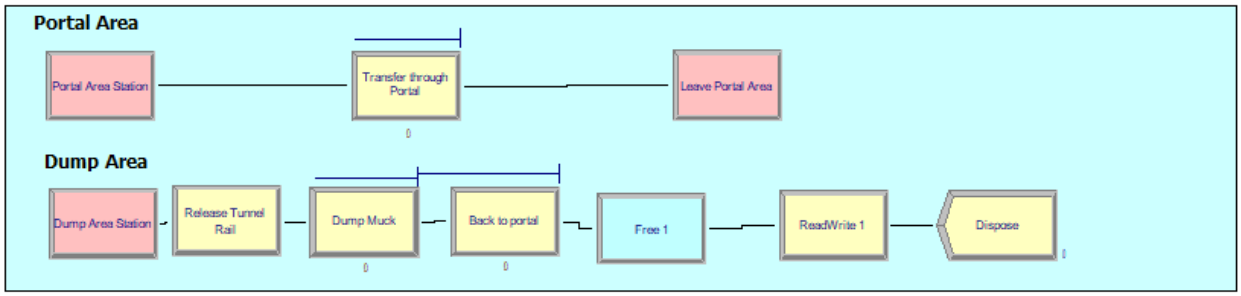


Figure 4.26. Activities at portal and dumping area in CSM2020 model

Portal and muck dumping area shows the transfer of muck from the excavated tunnel to the portal and then to the muck dumping station (Figure 4.26). The 'Transfer through Portal' is the time required by the muck car to reach the portal from the excavated length as discussed in the transportation chapter. The 'Back to portal' module consist of the time that is required for the train to come back from dump area to portal in order to go back to the TBM area. 'Free1' module sets the transporter as free or available in case of redundant capacity, meaning additional trains that can enter the tunnel, independent of muck train dumping the load at the muck pile.

The 'Readwrite1' module capture the results per stroke and exports it to the excel file which is later processed for estimating the overall utilization along with other factors like identifying the critical activities at various sections of the tunnel. The 'Dispose' is last module after which the model goes back to starting point to check whether the shift /tunnel length is over and then start the tunneling process.

4.5 Limitations

The CSM2020 encompass a significant set of tunneling activities that influences the utilization value. The addition of other modules as required is possible in this model. However, the model has certain limitations as listed here:

- The present model is valid only for the hard rock TBMs. The processes that happen in earth pressure balance and slurry TBMs are not included in the present model.
- The effect of change in diameter is not considered in the model as the data available had diameter range of 4.5 to 7 m and no significant variation in the process time was observed.
- The cutterhead parameters are not considered as separate factor for utilization estimation.
- The effect of TBM availability on the basis their condition is considered directly but is part of the routine maintenance module.

- The distinction of the double shield machine working as open or as single shield is not considered. The model assumes that the double shield machine will always have segment installation as a parallel activity. This is an easy fix in follow up work where the operation mode can be linked to RMR or other ground condition tags.
- The model assumes a shift of 10 hours and do not wait for the activities to complete. For example, if the utility extension is in between 2 shifts, the model assumes that this activity will partly be in one shift and rest in another. In most of the project sites, this assumption is valid as observed in Stillwater mine project.
- The model does not assume holidays and non-working days in the analysis, meaning that the results are based on working days.
- The transportation system via train or conveyor belt assumes a constant travel speed.
- The transportation of supplies is only via train and motorized rubber tire vehicles are not considered in the model, since their use is rather rare.

4.6 Conclusion

The present study was focused on providing a platform for utilization estimation wherein a variety of tunneling activities along with their interdependencies are modelled. The CSM2020 model is based on DES approach which provide a distribution of utilization that shows the stochastic behavior of the model. The various activities are fed into the simulation model as modules. The model is prepared for one stroke, which can be repeated to incorporate the effect of tunnel length. The model encompass the effect of crew, variation in the TBM types, requirement of probe drilling, utilities that are extended at certain intervals, combination of various ground support measures that are required as per the prevailing ground conditions, TBM face and backup delays that include electrical, mechanical, hydraulic delays. The model provides a provision to

choose the muck transportation system via conveyor belt or train (muck cars). Separate set of transportation related delays are included in the CSM2020 model like track replacement, unloading and loading of supplies, derailment, wait at California switch(es) among others. The California switches are activated as the tunnel length increases. The effect of TBM condition (whether new or refurbished) is considered in the maintenance modules.

The CSM2020 model provides utilization per stroke which is very useful in identifying the critical locations like change in ground behavior, the effect on addition of train and California switch, the effect of probe drill and utility extension among others. This aspect helps in identifying the bottlenecks in the tunneling activity that can ultimately be used for optimizing the performance of tunneling operation.

Hence, it can be concluded that discrete event simulation is a reliable method of predicting the TBM performance. The CSM model can be customized as per the TBM types and site-specific requirements. For generalization and use in other operations, sequence of activities can be bypassed or activated to obtain a consistent result.

4.7 References

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CHAPTER 5

SIMULATION OF TBM OPERATION TO ASSESS THE IMPACT OF GEOLOGY ON THE MUCK TRANSPORTATION

5.1 Abstract

Simulation of tunnel activities considering TBM to be a tunneling factory can be a reliable method for estimation of TBM utilization factor. The subsurface geotechnical conditions that control machine penetration rate and muck transportation system are the two most important technical factors affecting the overall performance of the machine in a routine operation. This section focuses on establishing the impact of geology on the muck transportation system to observe the interdependence between TBM penetration rate and transportation delays. The muck haulage system should be designed to incorporate the changes in the excavation rate in different geology to minimize related delays. The simulations were performed using discrete event simulation software, Arena©, where various tunnel activities were modeled in their relevant sequence with varying geological conditions. The simulation accounts for the number of trains and addition of California switch to examine the impact of the geological setting on transportation-related delays in various formations.

5.2 Introduction

Tunnel boring machines (TBMs) have dominated the tunneling industry since they were first introduced in 1950s and recent technological advancement have made them more efficient to meet increasingly challenging conditions and operational demands. Justifying the use of TBMs as the tunneling method and selection of machine type, specs and back-up system requires accurate assessment of anticipated productivity and performance of machine in given geological conditions.

There are several models for TBM performance prediction that allow for estimation of rate of penetration. The most commonly used models for this purpose include the Colorado School of Mines (or CSM) model, Field Penetration Index (FPI) model, and Norwegian University of Science and Technology (or NTNU) model (Xue et al., 2018). These models estimate rate of penetration (ROP). Different models are needed to estimate TBM utilization considering the machine downtimes and delays (Rostami, 2016). However, the available models for estimation of TBM utilization are insensitive to project specific parameters such as geology, machine characteristics, and site set up and do not account for all the individual tunneling activities and downtimes. This means that accuracy of TBM utilization factor estimated by available models is not very high. The details of shortcomings of these models are discussed by Farrokh (2012). Hence, there is a need to establish a model that is capable of estimating utilization factor considering site specific geological and machine parameters.

The rock mass condition has a significant impact on machine downtime and utilization factor (Frough et al., 2018). The muck transportation system and whole back-up system is designed according to the ground condition and project requirement. The table provided by Rostami (2016) shows general guidelines of estimation of TBM utilization for uniform and complex ground conditions and different muck haulage systems. However, this table is general in nature and does not take into account the intricacies of the machine, site set up and detailed geology.

The muck generated by the hard rock TBM excavation is generally well-graded and contains large elongated chips with low percentage of fines. If the excavation cycle of a given stroke is longer (i.e. in harder rocks), muck haulage system will have sufficient time for trip to the portal (or shaft), disposal, and return to the heading. As such, the operation does not incur any delays, whereas if the formation is softer and time for advancing a stroke is short, then trip time to

the disposal site may register as downtime and lead to lower utilization. This simple example shows how the ground condition could make transportation system the bottleneck in overall TBM performance. As pointed out by Faddick (1978), the transportation system is a potential limiting constraint in the TBM operation and therefore studying its impact under different geological conditions is important. As such, the focus of this study is to evaluate the effect of different ground conditions on muck transportation system using the recently developed discrete event simulation for modeling TBM performance in a given geological setting.

5.3 Transportation types

Muck transportation system plays a vital role in estimation of TBM utilization factor. The different types of muck transportation system include track bound logistics systems, trackless logistics system and conveyor belt. While haulage system from TBM face to the backup area is usually by a conveyor belt (TBM belt), the muck is carried through the tunnel to the dumping area by different means of transportation (tunnel haulage). Among the available options, the most commonly used tunnel haulage system is track bound logistics systems or simply, trains. The objective of studying the transportation system is to minimize the delay caused by tunnel haulage. This can theoretically be achieved by having the cycle time of one train less than or equal to the cycle time of one TBM stroke (Rostami et al., 2014). Table provided by Rostami (2016) shows that overall utilization rate is higher in case of conveyor belts when compared with train haulage system. The table also shows that utilization factor reduces with the complexity in the ground condition. However, the relation between the transportation system and ground condition suggested in the proposed table was not well defined and is general in nature.

5.4 Effect of geology on transportation

To represent the impact of ground conditions on TBM operation, it is assumed that with lower RMR value, the penetration rate will increase but considering the presence of joints and instability, the TBMs are driven at reduced thrust and RPM (Farrokh, 2012). Frough et al. (2018) established that highest utilization and lowest downtime can be achieved with RMR between 40 and 60 for the cases that were studied, where a double shield TBM was utilized for tunneling. In the case of open TBMs, the time required for ground control at lower RMR reduces the utilization factor and thereby advance rate. This in turn, gives more time for the transportation system to reach from portal to heading and vice versa, and thus it does not register as a downtime component.

5.5 Discrete Event Simulation Approach

The analysis was done by formulating a simulation model using Arena© which is discrete event simulation (DES) software. The simulation approach is proposed to minimize the uncertainties related to project logistics, resources, cost, time, and overall project management. DES provides flexibility and reduces the complexity of any system (Sharma, 2015) thereby proving a promising approach for simulating TBM operations. The model accounts for various tunneling activities that were set as events and inter-connected in series or parallel similar to real case scenarios. The simulation of transportation activity for a hard rock TBM was introduced by Rostami et al. (2014 and 2016) using Arena©. The proposed approach allows for optimization of the number of trains and California switches. Comprehensive simulation model was prepared by Rahm et al. (2016) depicting the activities of a mechanized tunneling operation. The models however did not incorporate different ground conditions, maintenance delays and other operational parameters and hence it was unable to predict the effect of geology on the transportation system.

In this study, a model is prepared for a double shield machine used in Karaj water conveyance

tunnel project in Iran (see Figure 5.1). The project had two sections with 16 km and 14 km long tunnels that was excavated using double shield TBM. The excavation and final diameter of the tunnel were 4.66 m and 3.90 m, respectively with 250 mm of lining thickness. The adverse geological conditions prevailing in the area was raveling, block failure, and some groundwater inflow (Frough et al., 2013). Different geological units with their average RMR values are listed in Table 5.1. . Details of Lot 1 (16 km) were taken for the analysis.

Figure 5.1. Double shield machine and site set-up for Karaj water conveyance tunnel project (Frough et al., 2014, 2018)

Time distributions related to each tunnel activity were prepared using Karaj water tunnel project – Lot 1 data. Tunnel activities include boring time and downtimes related to different geological conditions, transportation, segment installation, re-gripping, unexpected breakdown, maintenance, surveying, utility extension and muck disposal that are inter-linked on the basis of field observations. Data obtained from project site were analyzed to formulate time distributions of each tunnel activity. The best fitting curve with least square error was considered in the analysis. Example of time distributions for key tunneling activities are shown in Figure 5.2. Table 5.1 summarizes the time distributions of geology related delay for each geotechnical unit (Hassanpour et al., 2009).

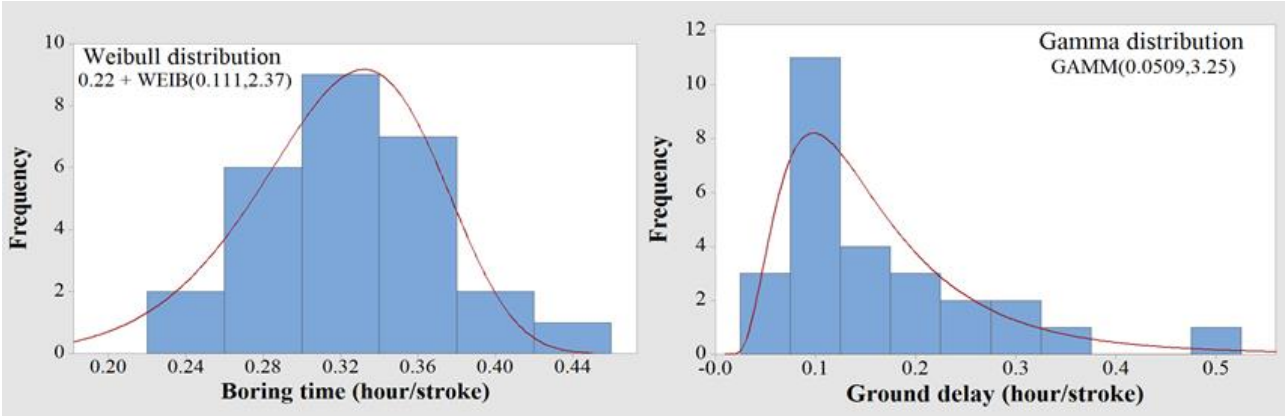

Figure 5.2. Example of time distributions prepared to be set as input for the simulation model.

Table 5.1. Engineering geological units encountered along the Karaj project alignment (Hassanpour et al., 2009)

Rock mass unit	Av. RMR	Remarks on rock properties and descriptions	Time distribution of ground related delays
Gta1-1	35	Weak to moderately strong rock, thin to moderately bedded, fractured	-0.001 + WEIB(0.596,0.245)
Gta1-2	50	Moderately strong rock, thin to moderately bedded, fractured	-0.001 + WEIB(0.0284,0.359)
Gta2	49	Moderately strong, thick to moderately bedded, moderately fractured, stable	-0.001 + EXPO(0.258)
Gta3	64	Moderately strong, thick to moderately bedded, moderately fractured	-0.001 + LOGN(0.298, 0.866)
Gta4	75	Very strong thick to moderately bedded	-0.001 + 10 * BETA(0.17, 4.16)
Sts1	57	Weak to moderately strong rock, thin to moderately bedded, fractured	-0.001 + EXPO(0.386)
Sts2	72	Very strong, thick bedded	-0.001 + WEIB(0.284, 0.736)
Mdg	63	Moderately strong, thick to moderately bedded, moderately fractured	GAMM(0.0509, 3.25)
Tsh	46	Weak to moderately strong rock, thin - moderately bedded, foliated, fractured	LOGN(0.242, 0.197)
Cz	21	Very weak strength, unstable rock	-0.001+143*BETA(0.0719,0.303)

5.6 Simulation Model

The main idea behind the simulation of tunneling operation with emphasis on muck transportation was to investigate the impact of train travel time. The cycle time of train less than or equal to that of one TBM stroke was not considered to cause delays. The simulation model was prepared in Arena© as shown in Figure 5.3. In total 19 models were prepared based on the increasing distance and varying geological units and number of trains to make the model compatible with the site conditions. The models showed good correlation with the recorded field data. The analysis showed that downtimes due to transportation and geology was 13% as shown in Figure 5.4. Five scenarios were considered to assess the interaction of geological and transportation related delay and the resulting overall utilization factor. The cases are:

Case I: 1 train with 5 different formations and related geology related delays

Case II: 2 train with 5 different formations and related geology related delay

Case III: 2 trains with 1 California Switch and 5 different formations

Case IV: 5 geological units arranged in different sequences with 2 trains

Case V: 5 geological units arranged in different sequences with 2 trains

For Cases I to III, the geological units selected were units Gta1-2, Sts-1 and Gta4 and RMR values were used as the base for the selection of these formations. The distance from the portal was kept same to compare the three cases. The top speed of the train for modeling was 14 miles / hour, which is typical of many muck haulage trains. The position of switch was kept the same i.e. behind TBM backup area. The total tunnel length was 6.5 km for all the cases.

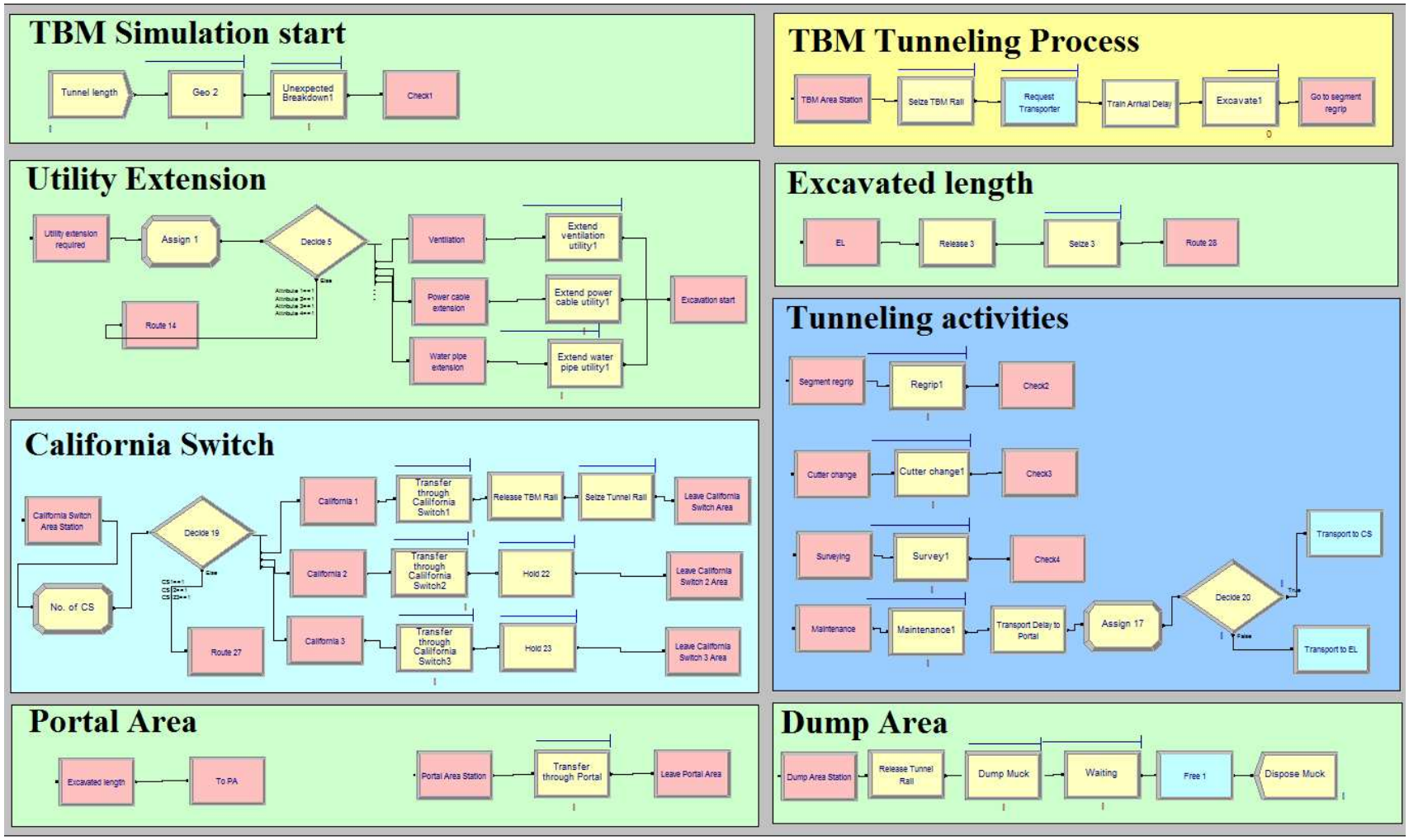

Figure 5.3. Karaj project simulation model in Arena©

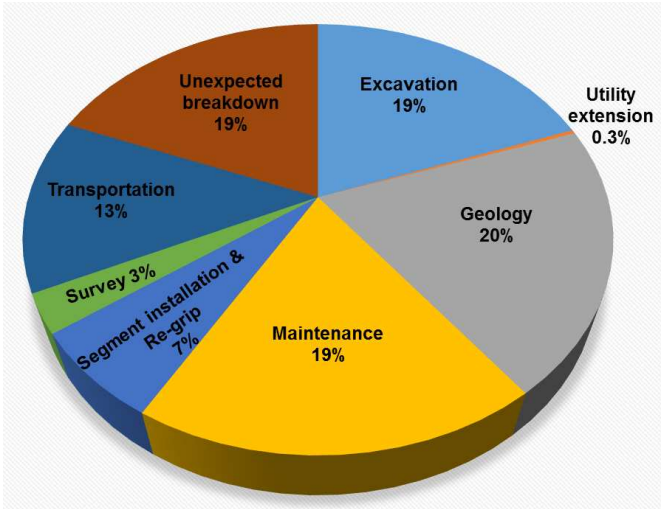

Figure 5.4. Karaj project overall downtime analysis

For Case IV and V, the effect of distance from the portal was analyzed with variable sequence of geological units. Two (2) scenarios were modeled and compared as shown in Figure 5.5. Two trains without California switch was considered for this analysis. Five geological units with variable length along the tunnel alignment was considered as given in Table 5.2. The total length of excavation simulated was considered equal to 6.5 km. The time distributions for boring, utility extension, maintenance, unexpected breakdown, surveying, regular maintenance, cutter change, and transportation delay were modeled as per field observations in Karaj project.

Table 5.2. Input parameters of geological units for Case V

Geological units	RMR	Time Distribution for geological delay	Time Distribution for Boring
G1	21	-0.001 + 143 * BETA(0.0719,0.303)	LOGN(1.13,0.943)
G2	35	-0.001 + WEIB(0.596,0.245)	LOGN(1.51,1.2)
G3	50	-0.001 + WEIB(0.0284,0.359)	0.1 + LOGN(0.303,0.0971)
G4	65	-0.001 + LOGN(0.298, 0.866)	0.22 + LOGN(0.123, 0.0497)
G5	75	-0.001 + 10 * BETA(0.17, 4.16)	0.04 + ERLA(0.0316, 11)

A total of 10 replications for each case was executed to obtain the resultant distribution. Time distributions were taken on the basis of tunnel length and geological conditions. The simulation model shown in Figure 5.3 was considered as the base scenario for the analysis for all the cases.

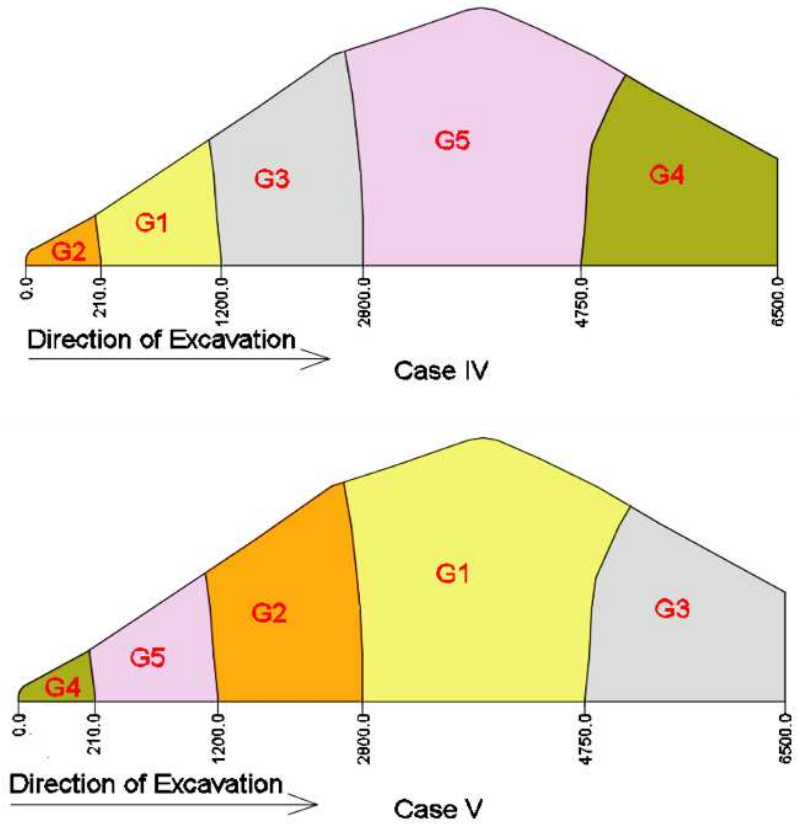

Figure 5.5. Different sequence of geological units along the tunnel alignment (Cases IV versus Case V)

5.7 Result & Discussion

In Case I, II and III, the delay due to transportation is inversely proportional to the geology related delays (see Table 5.3). At lower RMR, significant delays are caused by ground support issues in adverse ground where face collapse and increased maintenance of the cutter discs were

expected, which reduces utilization rates. Increase in RMR, especially when RMR goes higher than ~50 increases the utilization, and it plateaus around RMR ~70 (depending on other issues, especially rock strength and abrasion). These results are consistent with the trends discussed by Frough et al. (2018). When delays caused by adverse geology is the same, the difference in overall utilization rate as a function of transportation can be assessed and the impacts observed easily (Table 5.3). The average completion time reduces with addition of number of trains and further addition of California switch. The boring time remains the same but the overall percentage in time allocation increases as the transportation delay reduces. Significant reduction in the transportation downtime can be seen when California switch is added showing its significant applicability in the optimization of the TBM operation.

Table 5.3. Much transportation delays and its sensitivity to geology and transportation systems

Case No.	Transportation system	RMR 50	RMR 65	RMR 75
I	1 train	33%	32%	30%
II	2 trains	23%	22%	21%
III	2 trains + 1 California Switch	17%	16%	15%
Increased Utilization factor with change in transportation system		5%	3%	4%
Notes: The transportation delay is reduced to almost half, but utilization is not increased accordingly due to other delays being more prevalent.				

It should be noted that reduction in transportation related downtime does not directly translate to improved utilization, since other bottlenecks will surface as transportation system gets more efficient and causes less downtimes. Case IV and V: This case was focused on assessing the effect of sequence of variable geological units along the tunnel alignment considering similar transportation system. As can be seen from Figure 5.6 and Figure 5.7 that changing the sequence of units can significantly change the overall utilization factor of a TBM operation.

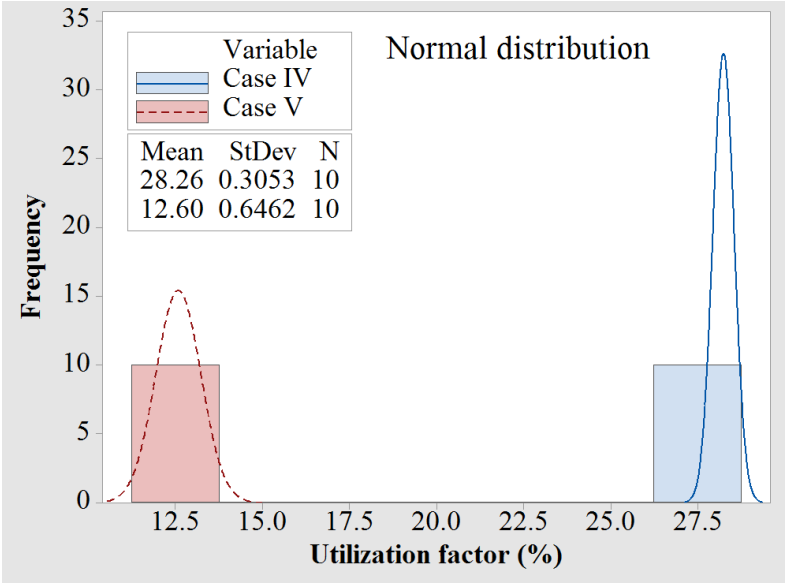

Figure 5.6. Utilization factor variability with change in sequence of geological units (Case IV versus Case V)

Considering one geological setting, it was observed that the utilization factor varied as location of the unit changed along the alignment. Units with RMR 65 and 75 resulted in lower utilization factors when they were near the portal. This is because the excavation cycle was faster and TBM had to stop for the train to arrive at the backup area thereby reducing the utilization. It must be noted that during initial excavation, the TBM operation is still under learning curve and many other activities lead to reduction in overall utilization factor.

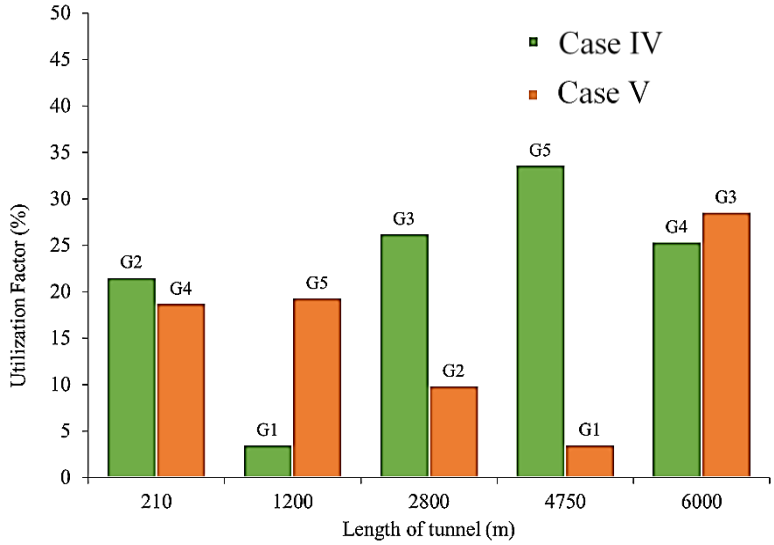

Figure 5.7. Case V: Utilization factor variability with change in sequence of geological units

5.8 Conclusion

The current study was conducted to assess the interaction between the geology and transportation system in TBM operation. Adverse geology represented by lower RMR values can have different effect on time for the train to transport the muck to the shaft or portal, depending on the site settings. In weak grounds, delays and lower utilization factor is mostly due to ground control issues. In the case that was modeled in this study, given the machine type and geological settings, as RMR value increased to ~70, the transportation system became the main bottleneck thereby contributing to increased delays in this sub-system. With further increase in RMR value, the rock mass becomes stronger and perhaps with high abrasivity, that causes longer boring cycles and while utilization factor might increase, the daily advance rate might be lower. The time allocated for the cutter inspection and frequency of cutter change increases in this scenario that could be the main component of delay i.e. geology. With additional number of trains and California

Switches, the delay due to transportation is reduced as the enhancement in the transportation subsystem will address the bottleneck and thereby increases the overall utilization of the machine.

The study shows that optimizing the transportation system by increasing number of trains and adding California Switch, increases the TBM utilization and hence notable reduction in the completion time can be realized. The sequence of geological formations along tunnel profile also impacts utilization factor, which is often very difficult to quantify using conventional performance prediction approaches. As such, the simulation approach allows for optimization of the transportation system, or perhaps other subsystems, for the geological settings and site arrangements.

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CHAPTER 6

UNDERSTANDING THE EFFECT OF GEOLOGY RELATED DELAYS ON PERFORMANCE OF HARD ROCK TBMS

6.1 Abstract

The performance of a rock TBM is assessed by its advance rate that is a function of penetration rate and utilization factor. While there are various existing models that can reasonably predict the penetration rate, only few models have the capability to accurately estimate the utilization factor, and the accuracy of models predicting utilization factor are highly dependent on the incorporation of complexities involved in different tunneling activities. The geology-related delays include the downtime incurred for ground stabilization, including installation of rock bolt, wire mesh, strap, or channel, laying of ribs or lagging, gripping process, control of water inflow, cutter change and inspection, probe drilling, scaling, muck removal, and foam injection for ground stabilization. This study aims at determining the most critical ground troubleshooting activity affecting the TBM performance using discrete event simulation. For this purpose, six projects that utilized open TBMs were analyzed. The results show that geology-related delays indeed contribute significantly to the variations in utilization factor, but the DES simulation approach allows for more accurate quantification of the related delays, given the specific site set up and geological sequences.

6.2 Introduction

TBM performance and daily advance rate is a function of penetration rate and utilization. In typical working conditions for open type TBMs, commonly used in rock tunneling, the machine utilization is typically in the range of 20-30% (Rostami, 2016). This implies that various other

tunneling activities directly or indirectly prevent the boring operation and hence affect the overall machine utilization. The impact of low TBM utilization on advance rate is much larger than the impact of penetration rates, and therefore reliable estimation of utilization becomes a crucial task (Tarkoy, 2009). Maidl and Wingmann (2009) emphasized the importance of precise recording of stoppage time or delays, while Scheffer et al. (2014) gave prominence to implementation of flexible simulation models with sensitive interaction of different processes for accurate estimation of machine utilization.

The existing performance prediction models include the Colorado School of Mines or CSM model by Sharp and Ozdemir (1991), Norwegian University of Science and Technology or NTNU model by Bruland (1998) later updated by Macias(2016), the Q_{TBM} model by Barton (2000), the rock mass excavability index (RME) by Bieniawski et al. (2007) and an empirical model by Farrokh (2012). These models, however, do not incorporate all the tunneling activities required to accurately estimate the machine utilization and therefore some inaccuracies in the estimation is expected. Use of discrete event simulation by Abd Al-Jalil (1998) and Frough et al. (2019) have shown the capability of this approach to incorporate the complexities involved in the estimation of machine utilization. The present study uses this approach for analysis of the impact of various geological and rock conditions on machine utilization, given the machine specifications and site set up and logistics.

6.3 Ground Related Delays in TBM Tunneling

The performance of TBMs is highly dependent on geological conditions present at the site, like rockfall, spalling, water inflow, squeezing, rock burst, excessive abrasion among other factors for hard rock tunneling (Delisio et al, 2012). The collapse of the face and crown or sidewall failures causes downtimes due to cleaning of face and invert and installation of support measures like wire

mesh, bolts, channel and ribs required for given rock mass, excessively abrasive ground causes increased frequency of cutter wear and delays are caused due to cutter maintenance and replacement. The presence of water may cause delays, especially if grouting becomes necessary to control the inflow in the tunnel (Frough and Rostami, 2018). The flowchart shown in Figure 6.1 illustrates some adverse geological conditions and possible methods for troubleshooting. It is clear that ground related issues significantly influence the machine utilization.

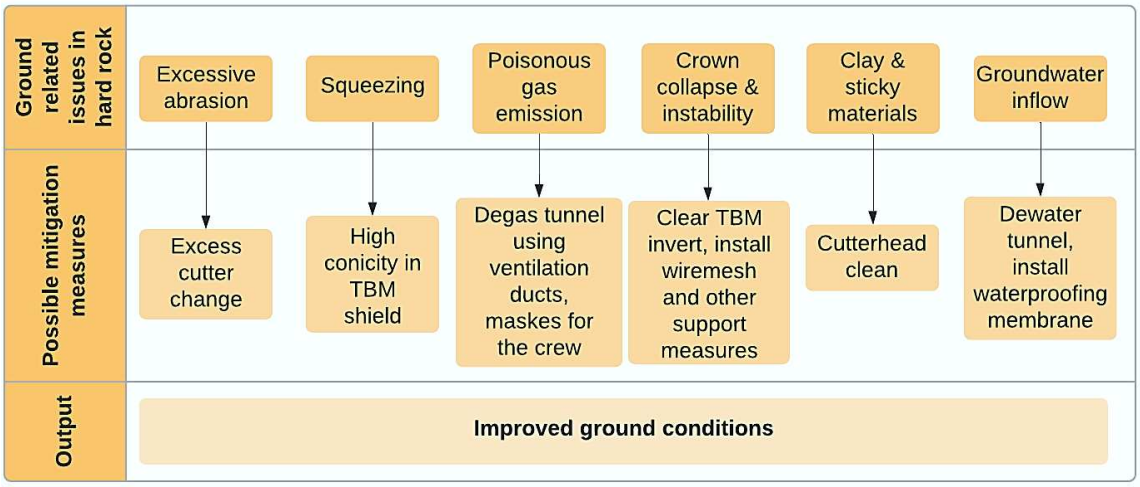

Figure 6.1. Ground-related issues and its possible troubleshooting measures of hard rock

The sensitivity of machine utilization to variations in RMR values of geotechnical units was analyzed by Khetwal et al. (2019) and the results showed that the sensitivity becomes negligible for lower RMR values and maximum variation in the result is observed for good quality rock mass. However, no details were provided regarding the troubleshooting measures used to stabilize the ground. The effect of means and methods of muck disposal on utilization was studied by Jencopale (2013) and the effect of geology was studied by Khetwal et al. (2019). Namli et al. (2014) studied a metro line project in Turkey and found that past experience in complex geology plays a vital role in determining the learning curve for predicting the performance of a machine.

6.4 Discrete event simulation

Successful planning of any construction project with further enhancements can be achieved using a simulation approach (Touran and Asai, 1987; AbouRizk et al., 1999; Rawanpura and Ariaratnam, 2007). Simulation models are considered to be opportunistic tools that allow the exploration of "what-if" scenarios (AbouRizk, 2010; Al-Bataineh, 2012). Contributions in terms of comparison of alternatives for project selection, planning, scheduling and estimating and construction planning are made using simulation approach (Rawanpura and Ariaratnam, 2007). Sawhney (1997) used the perti net based scheduling technique to simulate the dynamic aspect of construction project. Shi (1999) and Martinez (2001) proposed an activity-based construction (ABC) modeling and simulation to account for dynamic and random behaviors and construction processes that are considered as a limitation for critical path method. Copur et al. (2014) analyzed a stochastic model using Monte Carlo simulation to predict the machine utilization time using linear cutting test data. Liu et al. (2014) studied the Jingping hydraulic tunnel in China to predict the performance of a TBM using cyclic operation network simulation and found a high risk of delays due to ground issues. They suggested the possible implementation of ground-related uncertainties in the simulation model. The interaction between the TBM and ground was found to be the key factor by Maidl and Stascheit (2014) using computer-based data management system for optimization of the tunneling process.

Discrete event simulation aims at modeling operations of a system as discrete events and provides flexibility in variety of problems (Sharma, 2015). Implementation of discrete event simulation (DES) methods in construction operations was studied by many experts such as Oloufa (1992); Ben-Awuah et al. (2010); Botin et al. (2015); Dang et al. (2018); Kim et al. (2018). Donghai et al. (2010) used CYCLONE simulation software while Frough et al. (2019) used DES

and Arena© software, and Duhme (2016) used Anylogic as a simulation tool to model TBM operation.

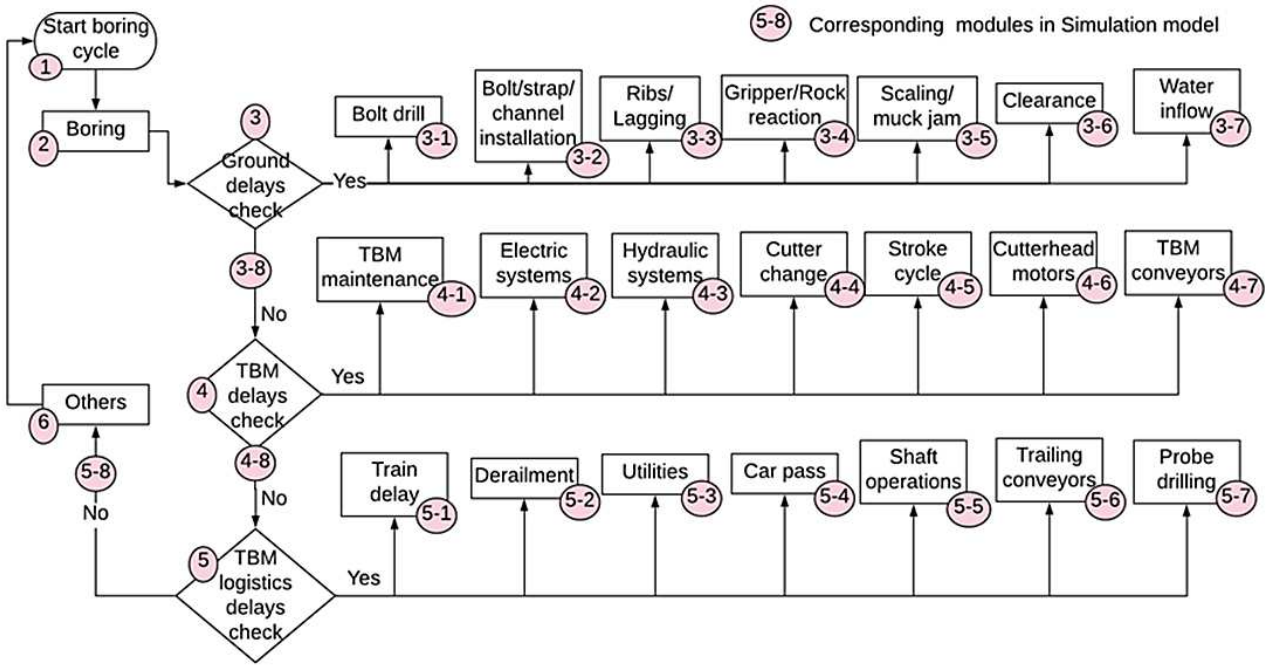

Figure 6.2. Flowchart for simulation model

6.5 Methodology

The present study aims at understanding the impact of critical ground-related issues affecting the overall performance of TBM. Six projects were considered for analysis as discussed later in this paper. The flowchart shown in Figure 6.2 was prepared pertaining to data available for analysis, and this was used as base for the simulation model as shown in Figure 6.3. using Arena© software. The TBM operations were simulated only for whole tunnel length, as detailed descriptions of the variation in geological units along the tunnel length were not provided. Time distributions were prepared using the input analyzer in Arena© for individual activities and their goodness of fit was checked using Chi-square and Kolmogorov-Smirnov tests as were used by

Frough et al. (2019) and Khetwal et al. (2019). A total of 50 replications were performed to obtain a stochastic distribution of the utilization and delays, and to consider the uncertainties in the input parameters. The details of the individual ground support measures were obtained and compared with the actual site data. The critical activity for each project was also identified and input into the DES simulation approach to determine the overall performance of the machine.

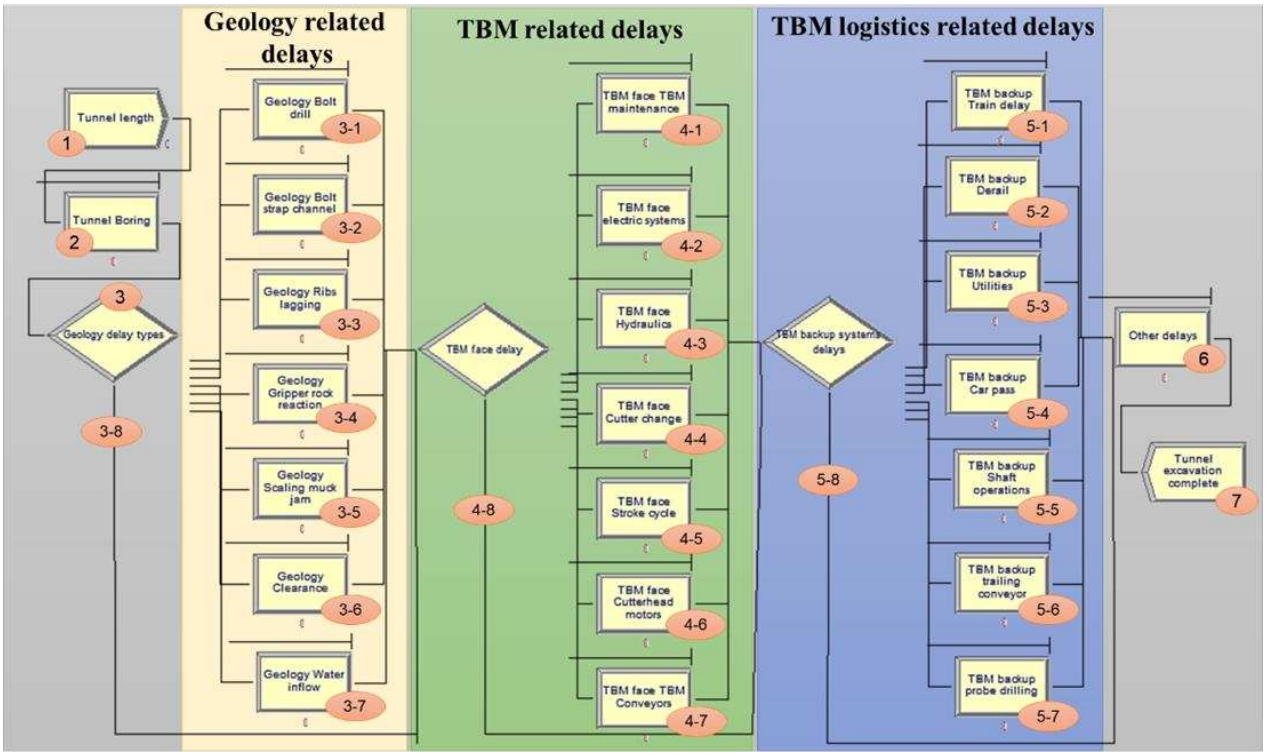

Figure 6.3. Modules for the Simulation model prepared in Arena©

6.6 Case study

The evaluation of the effect of geology-related delays on machine utilization was performed using data from six projects given in Nelson (1983). These are C11 outbound and inbound tunnels, C31 inbound and outbound tunnels, the Culver-Goodman tunnel and one of the Chicago TARP tunnel projects. Unshielded or main beam open type TBMs were used in all the

projects, and the excavated diameters ranged from 4 to 6.5 m. The details of the six projects are given in Table 6.1.

Table 6.1. Project details (Nelson, 1983)

Project name	C11 outbound tunnel	C11 inbound tunnel	C31 outbound tunnel	C31 inbound tunnel	Culver-Goodman tunnel	Chicago TARP
Tunnel length (m)	3,111	3,112	2,076	2,025	5,058	7,261
Tunnel diameter (m)	5.6	5.6	5.7	5.6	4.0	6.5
Geology-related downtimes (%)	21	17	21	16	29	12
Total downtime (%)	68	64	69	71	64	65
Average utilization (%)	32	36	31	29	36	35

The C11 and C31 projects were excavated in Buffalo, NY. The geology at the sites were a sequence of glacial deposits overlying Lower Paleozoic sedimentary rocks. The C11 and C31 tunnels alignments mainly run through the Bertie Formation which consists of dolostone, dolomitic limestone and dolomitic shale having thickness of 10.7-18.3 m. The four members of Bertie Formation are youngest to oldest the Williamsville, Scajaquada, Falkirk and Oatka. The Williamsville member is 1.5-2.4 m thick, gray to tan, medium to massive bedded fine-grained dolostone, while Scajaquada is 0.9-3.0 m thick, gray, thin to medium bedded, medium-grained argillaceous dolostone. The Falkirk member is 5.5-7.6 m thick, dark gray to brown, medium grained dolostone, massive with thinly bedded with undulating shale partings. The oldest member, the Oatka, is composed of dark gray, medium-grained dolomitic shale and medium to thinly

bedded having thickness of 1.5-2.4 m and higher joint frequency than observed for the Falkirk member. The average unconfined compressive strength of rock of the Bertie Formation was 166 MPa having RQD of 79%. During construction, heavy inflows of water were encountered, and a deep well dewatering system was installed to lower the groundwater table.

Major geological issues for the C11 tunnels were heavily jointed rock and high water inflow. Installation of steel sets, rock jams, scaling, gripper difficulties and clearance of trailing gear caused major geology-related downtimes. A total of 63 and 60 cutters were changed for the C11 outbound and inbound tunnel excavations, respectively (Nelson, 1983).

The C31 outbound tunnel had installation of steel sets as the major downtime associated with geology, as the tunnel was exposed to heavily jointed and weathered rock. For the C31 inbound tunnel, downtimes were also caused due to bolt drill repair. A total of 29 and 43 cutters were changed for the C31 outbound and inbound tunnels respectively (Nelson, 1983).

The Culver-Goodman tunnel project alignment crosses seven stratigraphic units: The Irondequoit limestone, Williamson shale, Lower Sodus shale, Reynales limestone, Maplewood shale, Thorold sandstone and Grimsby sandstone. These beds striking approximately east-west and dip to the south at about 12-15 m/km. The details of these formations are given in Table 6.2. The installation of steel sets, scaling loose rock and removal of muck jams from cutterhead buckets were major geology-related downtimes due to presence of heavily jointed rocks in some areas and overbreak in the crown tunnel sections with shale. A total of 810 cutters were changed during the Culver-Goodman tunnel excavation primarily related to the presence of highly abrasive rock (Nelson, 1983).

The rock formations at the Chicago TARP tunnel project in the Chicago, IL area strike north to north-east and dip to the east or southeast at 1.9 to 2.8 m/km. The project geology consists

of dolostone and shale deposits. The tunnel is predominantly excavated in the Markgraf member of the Joliet Formation and the Kankakee Formation. The Markgraf member rocks had an average UCS of 174 MPa while Kankakee Formation rocks has an average strength of 153 MPa. The accumulation of water at the heading was the major geological issue for this tunnel. A total of 335 cutters were changed during this excavation, and this project was the longest included in the study.

Table 6.2. Culver-Goodman tunnel project geological details (Nelson, 1983)

Formation name	Lithological description	Average UCS (MPa)	Average RQD (%)
Irondequoit limestone	4.6-7.0 m thick, light gray, thin to medium bedded, medium to coarse grained limestone	123	91
Williamson shale	1.8-3.0 m thick, dark green shale with thin limestone beds	82	81
Lower Sodus shale	4.6-5.5 m thick, green or purple, moderately to thinly bedded fossiliferous shale with occasional limestone seams	74	80
Reynales limestone	Wallington member: 4.3-4.9 m thick, thin to medium bedded, crystalline, dolomitic limestone Franceville member: 0.3-0.6 m red, oolitic, hematite limestone Hickory corners member: 0.5-0.9 m limestone and shale interbeds	147	83
Maplewood shale	4.6-6.4 m thick, green, thinly bedded shale	65	80
Thorold sandstone	0.3-0.9 m thick, fine-grained, cemented sandstone	130	90
Grimsby sandstone	17 m thick, red and green mottled, fine to coarse-grained, well cemented, medium to massive bedded sandstone	134	94

6.7 Simulation Model

The input data in the form of published graphs were obtained from Nelson (1983) and analyzed to prepare the time distributions for different activity modules as shown in Figure 6.3. . The frequency of occurrence of these events or downtimes were counted along the tunnel length.

50 replications were performed, and average values were compared with the actual data available. The verification of simulation models with field observations are necessary for validation of the simulation method and linkages used in the model, prior to its implementation to other projects (Nido et al., 1999).

The comparison of the results was made in the form of pie charts as shown in Figure 6.4. . The delays due to TBM backup system, maintenance and other activities were compiled together as "others." The geological downtime included delays due to bolt drill repairs, installation of bolts/straps/ channels, installation of steel sets, gripper rock reaction, face and invert clearance, water inflow and cutter change. The machine utilization is shown as "boring" in Figure 6.4.

The simulation results of geological downtimes for C31, C11 outbound and Culver Goodman tunnel showed overestimation of 1-2% while for Chicago Tarp and C11 inbound tunnels, underestimation of 4% and overestimation of 6% was observed respectively. This change was mostly accommodated in other downtimes as ~2% variation in utilization was realized. To assess the discrepancy in the results of geological downtimes, further detailed analysis was performed to identify the ground related issues showing maximum variation and to identify the critical factor affecting the overall machine utilization. The details are presented in Figure 6.5 From this information, it can be noted that for Chicago TARP tunnel, the cutter change delays showed major variation of 8.5% against actual 5.5%. The discrepancy in the result was due to unavailable data for all the cutter replacements and repair as noted by Nelson (1983).

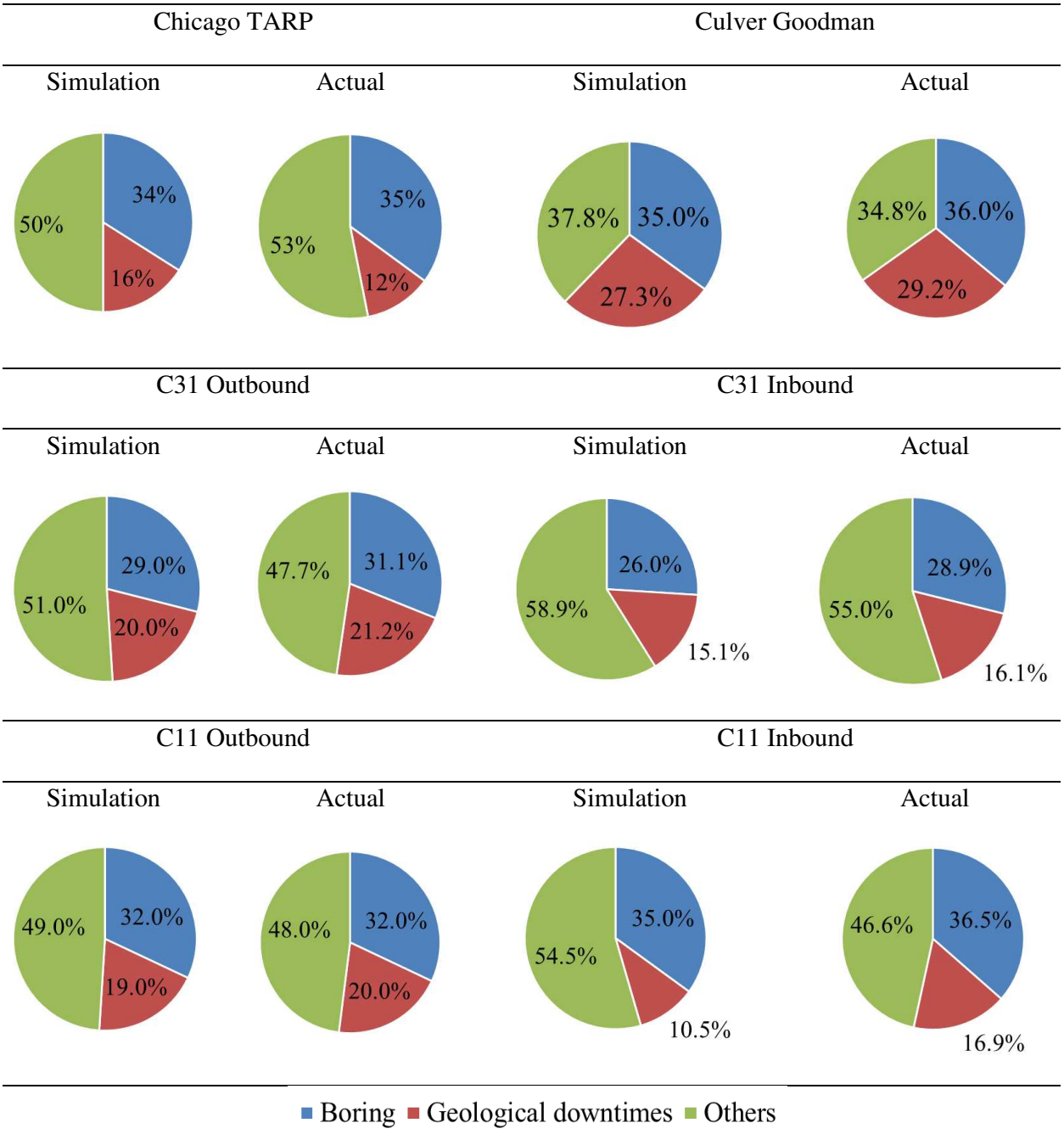

Figure 6.4. Comparison of simulation and actual results

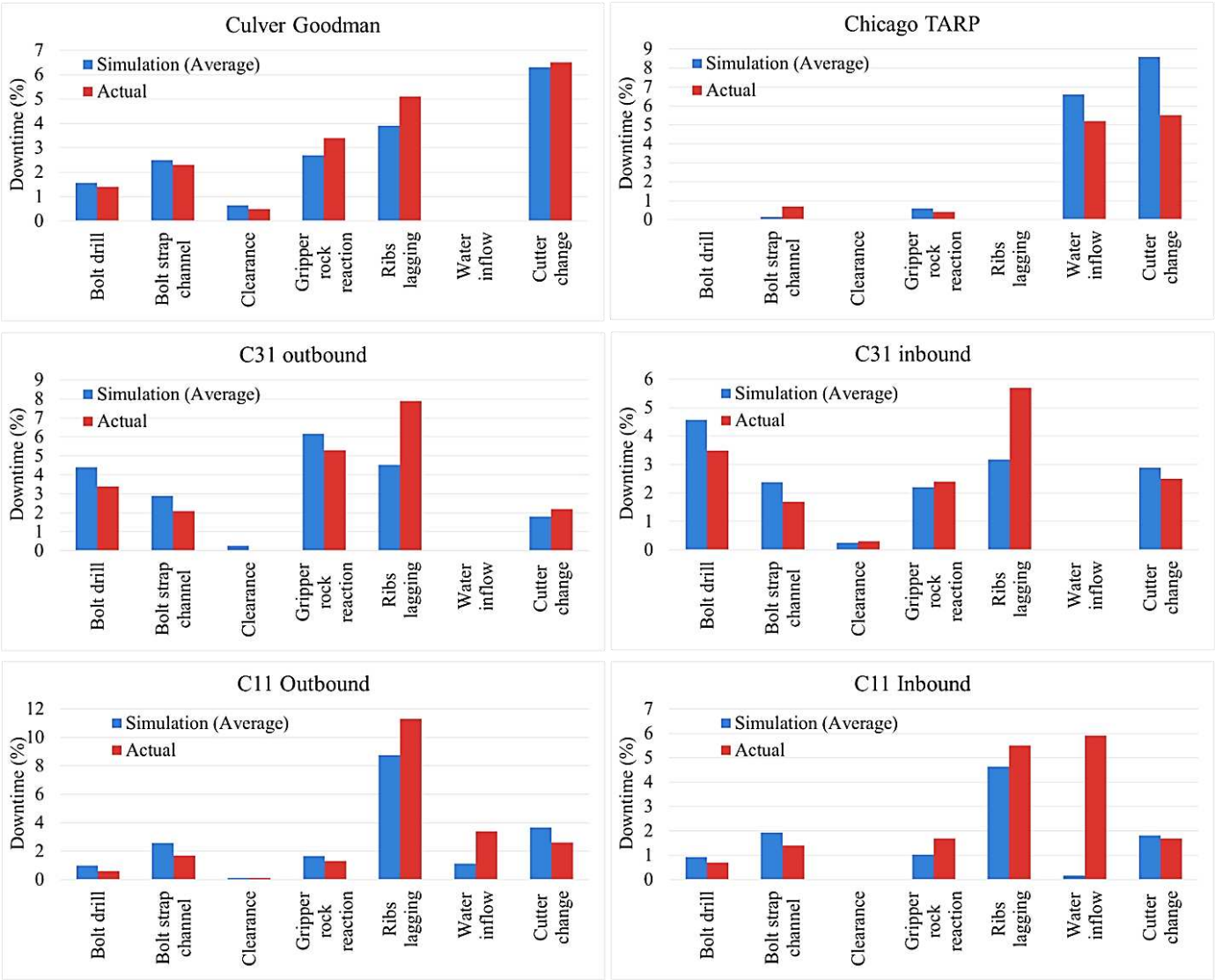

Figure 6.5. Comparison of actual and simulation results for ground troubleshooting

For the C11 inbound tunnel, the water inflow showed a variation of 0.2% against the actual 5.5%. As was indicated by Nelson (1983), the details of the impact of water inflow and flooding in the tunnel were not sufficient to input in the simulation model – this caused a discrepancy between the simulated and actual downtime records. This dissimilarity was also observed for ribs lagging for C31 tunnels. Therefore, the study also showed that efficient data logging is very important to analyze the possible critical factors affecting the utilization of the machine.

Overall, it can be seen that for the six projects analyzed, installation of steel sets and overcoming water inflow issues in open TBMs are the two critical factors affecting the overall performance of the machine. In the presence of highly abrasive ground (as seen in Culver Goodman tunnel), the delays due to cutter change act as a critical element, after ground support installation issues

6.8 Conclusion

The present study was conducted to examine the use of simulation modeling to predict the impact of various geological downtimes on machine utilization. Analysis of six projects using the discrete event simulation approach showed that simulation model is capable of encompassing all the different tunnel components that affect the overall performance of the machine.

To predict the influence of various geological issues to be encountered along the tunnel alignment, a detailed study of the prevailing geology in the area is paramount. Based on the available data, the simulation provided acceptable results. While utilization showed variation of ~2%, geological downtimes showed average variations of ~1-2% with the exception of the Chicago TARP and C11 inbound tunnels. The variation in the results showed the necessity of having access to accurate data logging for future projects. The overall analysis presented installation of steel sets as the major geological downtime for most of the projects, with an average

value of 7%. The Chicago TARP tunnel showed only 2% downtime due to installation of ground supports reflecting the stable ground overall, but on the TARP project there were major downtimes due to water inflow and cutter change. Water inflow was encountered for three projects presenting an average downtime of 4.8%, while cutter change showed an average of 2% downtime with exception of the Chicago TARP and the Culver Goodman tunnels.

The present study can be extended to assess the effect of other tunneling activities on the tunneling operation in a given lithological sequence and to predict the critical activities that involve the crew efforts during geological downtimes. The analysis done in this paper can be used for other projects considering the similarities in the projects and their ground related issues. The results can be used for prediction of TBM performance and development of project completion time, as well as identification of the bottlenecks in the operation where the changes machine backup or site set up and logistics can improve the tunneling productivity.

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CHAPTER 7

INVESTIGATING THE IMPACT OF TBM DOWNTIMES ON UTILIZATION FACTOR BASED ON SENSITIVITY ANALYSIS

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7.1 Abstract

The number of TBMs utilized over the past decade has escalated, testimony to their continuing success and flexibility for application on projects of different diameter, length, and ground conditions. There are various guidelines available for TBM selection and for developing a suitable specification for a machine for a given project. Proper application of these guidelines is an essential part of machine selection to assure optimal performance of these machines in a given project. However, available guidelines are very general in nature and based on past experiences: they cannot take into account the many intricacies of a specific upcoming project including site set up and geology.

This paper discusses use of Discrete Event Simulation (DES) to model tunneling activities and demonstrates the ability of simulation to capture the interrelationships between the TBM, back-up system, and geologic interactions. The simulations provide insight into expectations for utilization of individual components as well as overall TBM system utilization.

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The simulation model can be constructed to enable estimation of the machine utilization under various site set up and back-up arrangements, and thus paves the way to quantitative assessment of the value of adding different capabilities on the machine and back-up system. Case studies are used to demonstrate the impact of some common tunneling activities in different ground conditions. DES was used to study the effect of eight different tunneling activities on the overall performance of the TBM. Significant differences in productivity can be seen by varying the specification of the TBM and system components. The results show the importance of selecting the right components for the back-up and their impact on overall machine utilization, leading to the possibility of allowing more methodic and fact-based selection of system components for optimal TBM performance.

7.2 Introduction

Current trends and main challenges in tunneling industry are to go "faster-larger-deeper-longer". The success of tunnel boring machines (TBMs) in recent projects proven the use of TBMs to be a promising approach to meet these challenges. Performance of the TBM in each project is represented by the advance rate, which is a function of penetration rate (PR) and utilization factor (U). Both PR and U parameters are impacted by the ground conditions and operational parameters, while U is also impacted by site set up, maintenance, ground control, and experience of the crew. The typical value of U ranges from 5% to 55% with most common range 20-30% (Rostami 2016). This indicates that typically TBMs work only for a few hours per shift, with the rest of time being recorded as downtime involving in other tunneling activities. Paltrinieri (2015) noted that utilization factor estimation requires combination of both ground conditions and/or machine factors. The estimation of U requires careful consideration of the various tunneling activities occurring at the project site including machine maintenance, ground support, surveying, muck

transportation systems, cutter change, unexpected breakdown, etc. Interdependence among these various activities make the estimation of U a complex process. A general schematic diagram depicting the components of TBM and project are shown in Figure 1.1.

Various empirical performance estimation models have been introduced over the years for prediction of PR and U, and the input parameters considered in these models. The list indicates that most of the available models do not and cannot account for some of the critical activities on the job site. The present study aims at identifying the most critical activities that affect machine utilization and the magnitude of such impacts. The results can help in assessment of the workflow in a TBM tunneling operation such as the muck transport system (e.g., number of trains, speed, number and location of California switches), and other activities that might be performed in parallel including ground support installation and invert cleaning, laying rails, among other things, that directly influence the machine utilization. This approach also allows for quantitative assessment of impact of various features on the TBM and back-up system components and their impact on machine utilization, and therefore paving the way for more objective evaluation of these components in the process of machine selection and developing related specifications.

The necessity of determining the critical activities affecting the performance of TBM can be recognized by understanding the way each activity influences the utilization factor and hence machine's average daily performance. The details of some of the most frequently cited downtime categories are discussed in this section. Home (2018) stated, "*correct specification of TBMs can make all the difference on a project's success.*" Shahriar et al. (2008) listed six tunnel projects from all over the world in which inappropriate excavation techniques caused huge time and monetary losses. The correct choices of TBM type, along with proper specification of back-up features are critical for the system to handle anticipated difficult ground conditions. The 23.65 km

long, 6.18 m diameter HRT (Kishanganga) project was constructed successfully in the Himalayas using a double-shield machine, mining through andesite, phyllitic quartzite, meta-siltstone, and sandstone rock formations. The TBM was designed to accommodate the high squeezing ground with 43,500 kN of auxiliary thrust, high shield conicity and capability to implement variable overcut on the head. The TBM also had 2520 kW of cutterhead power to cope with unstable tunnel face (Goel, 2016).

A Mumbai water tunnel project (8.3 km long, 6.25 m diameter) used a main beam TBM and proved to be successful in spite of experiencing significant ground related challenges. The project achieved an average advance rate of 870 m/month that serves as a record for TBM tunneling in India. The TBM was equipped with probe drills that allowed grouting, a rock support system consisting of wet shotcrete spray system, and a ring beam erector that stabilized the rocks and ultimately reduced the downtimes providing more production time (Andhere, 2018).

These examples suggest that appropriate design and specification of the excavation systems to enable smooth workflow plays a very important role achieving reasonable TBM performance. In the increasing number of cases where the same TBM has to mine extended length of tunnels, a systematic and quantitative assessment of machine performance has become very valuable. Yet, there is no model currently available that can look at the actual performance of a given TBM in a tunnel project with a sequence of different formations to be encountered, and offer a precise evaluation of anticipated machine performance, considering different types of machines and back-up systems. This paper discusses the development of a process simulation approach to model TBM system tunneling activities that allows to study various operational scenarios with consideration of machine specifications and ground conditions. To show the capability of this approach, a comparative study of the various excavation system components and activities is presented to

document the effects on the overall TBM utilization for a given geological condition. Discrete event simulation method is used to simulate the different activities of the excavation system with the capability of stochastic forecasting system operation, where a range of different variables are used to assess the sensitivity of the modeling and the whole system to such variations and to measure their impact in various scenarios.

7.3 Discrete Event Simulation (DES)

The operation of a tunnel excavation system is much like any other production line in various factories and manufacturing processes. Production involves a series of individual activities in series or in parallel that have to happen in a certain sequence to allow for making the efficient productivity, in this case footage of tunnel mined and lined. As such, these activities can be modeled in a simulation program that defines the correct sequence of steps for achieving the end goal. AbouRizk (2010) proposed that simulation could serve as an opportunistic tool for all construction management issues. The duration required for any individual activity is not a fixed value and has a random distribution. Therefore, at the heart of every stochastic simulation model, there is a mechanism for generating values for the random variables that influence the behavior of the system being analyzed. Monte-Carlo simulation includes a random-number generator that is suitable for simulating both probabilistic and deterministic problems (Pegden et al., 1995). The development or evaluation of complex systems can be done using various forms of simulation methods, thereby providing better understanding of processes (Vieira et al., 2017). Such simulations may be conducted for variety of purposes like system evaluation and their comparison, prediction of the system performance and output, sensitivity analysis, establishing the nature of relationships between significant factors and bottleneck analysis, among others (Pegden et al., 1995). Ruwanpura et al. (2004) proposed a simulation template to predict the soil conditions that

can reduce the uncertainty and improve the productivity of the tunnel construction operations, thereby establishing the potential of simulation in tunneling industry. Discrete event simulation (DES) is defined as an approach to simulate events that occur in sequences presenting its influence on other events. Sharma (2015) and Oloufa et al. (1998) reviewed the advantages and disadvantages of simulation and found that the DES provides a lot flexibility and hence can be used for wide variety of applications including job-shop scheduling, comparing the energy consumption of a manufacturing systems, assessing the delay in patient transit at major hospitals, evaluating the supply levels of blood in hospitals during mass casualty events, and integrating 3D visualization components to simulate movement of mobile cranes at a construction site. Use of DES in simulation of mining operations is fairly well established. Some examples include open pit production scheduling; short-term production planning and optimization of open –pit mines, dispatching strategies, and plant proactive decision-making. In this study, DES modeling is used for simulating the tunneling activities and operation to see the influence of the capacity of various components on the entire system.

Recent implementation of DES include assessment of the impact of disturbances and different soil compositions on productivity using AnyLogic by Dang et al., (2018), prediction and evaluation of the performance of variable production line using Arena© by Li et al., (2018), combined study of construction process simulation using WebCYCLONE and vision-based context reasoning to automate the productivity assessment for an earthmoving process in tunnel (Kim et al., 2018) and evaluation of different strategies using DES for red blood cell provision during mass casualty events by Glasgow (2018). Jalil (1998) first used discrete event simulation (DES) in estimation of utilization factor wherein a set of 10 input parameters provided a stochastic distribution of completion time. Simsuper software and FORTRAN code were used to estimate

the utilization factor. This approach, however, did not consider all the tunneling activities required for the estimation and mainly focused on the geological variability along the tunnel alignment. Frough et al., (2019) and Rostami (2016) presented a methodology of predicting the utilization factor using DES approach. Frough et al., (2019) discussed use of discrete event simulation (DES) for evaluating different tunneling operations. The delays associated with different tunneling activities were given in terms of their respective time distributions that were analyzed in a combined arrangement to estimate the utilization factor. Duhme (2017) used SysML, a DES software to simulate the various tunneling processes. The above methodology of using DES for the estimation of utilization factor proved to be a promising approach considering its accuracy and easy applicability for other similar projects.

Decision Aids for Tunneling (DAT) is yet another method using discrete event simulation for estimating the total cost of tunnel with reference to the total construction time incorporating the uncertainties related to geologic conditions, construction processes and resources (Einstein, 2002). The performance of equipment and the tunnel workforce along with unforeseen construction events lead to uncertainty in the advance rate. The variability in the range of total construction time vs cost can be assessed using DAT (Halabe, 1995). Analysis of the Piora zone in the Gotthard base tunnel by Dudt et al. (1999) showed relevance of DAT in assessing the risk associated with the geological conditions. However, the construction related issues were not emphasized and therefore further elaboration of the approach is required. The applicability of DAT is best suited in the design phase wherein different tunnel alignments and construction methods can be compared that can be used for construction management. For example, updating the design of the Sucheon tunnel in Korea showed the relevance of understanding construction related uncertainties in determining the project cost needed to be related to the existing geology (Min,

2003; Min et al., 2008). Min and Einstein (2016) used the DAT computer code to prove the significance of resource allocation for reducing the overall construction cost of a project. However, the limitation regarding the representation of activities and effect of distance in resource handling is mentioned by Min (2007). The present study aims at identifying the effect of individual resources that directly or indirectly impact on the overall performance of the machine.

In the present study, Arena©, a commercially available DES software is used. As suggested by Oloufa et al. (1998), a simulation library is present in the software that allows modeling a variety of project scenarios. The software encompasses wide variety of scenarios that support detailed analysis of the manufacturing system, supply chains, transportation and logistics systems, identifying process bottlenecks and over-utilization of resources (Allen-Bradley, 2014; Allen, 2011).

7.4 Sensitivity Analysis

Sensitivity analysis holds a significant importance in a variety of computational engineering problems and can be used to quantify the difference in the output due to small changes in the system parameters. In addition, the interdependence, biases, and inaccuracies of the modeling and simulation approach can be assessed by representing a complete functional system. The effect of individual delays on the construction duration for a tunneling project was studied by Werner and AbouRizk (2015) where the sensitivity analysis was performed by removing individual delays and checking the variation in the production rate and project duration. Three delay categories were the most influencing parameters in terms of productivity and costs: the condition of rock and voids, PVC as built delays, and TBM hydraulic subsystems.

Local sensitivity analysis (LSA) is performed when one parameter or process is changed in an integrated system model while keeping the other parameters fixed to a set of specific values.

LSA is unable to quantify the effect of interactions among parameters, and this may be too important to neglect. Global sensitivity analysis (GSA) can estimate both global and main sensitivity indices by estimating the contribution of each parameter to the system performance (Liu et al., 2017 and 2018). In GSA, all the input parameters are varied simultaneously, and sensitivity is evaluated over the entire range. GSA allows quantification of the overall effect of inputs on outputs and provides a more realistic results considering the non-linear relationship between the input parameters. In this study, LSA is performed to identify the effect of individual tunneling activities on overall performance of the machine. GSA was not performed as the main aim of this study was to identify the extent of influence of individual activities on the overall performance of machine.

LSA is used to quantitatively assess the impact of input parameter as deterministic or random variable. Transparent assessment of utilization of logistics and project set up can be achieved by process simulation (Scheffer et al., 2014). The output from a sensitivity analysis for the stochastic simulation depends on the number of replications, as lower number of replications often are unable to show the full breadth of impacts caused by changing parameters on the system. The sensitivities to output parameters become more pronounced when the replications are increased to certain extent. This is to be expected in DES modeling where after a certain threshold is met, the number of replications does not add much to the accuracy or sensitivity of the models. In this study, the results of replications were checked for 5, 10, 25, 50, 100, 500 and 1000 replications, and an asymptotic result was obtained after 50 replications. Therefore, in the present analysis, the number of replications was limited to 50.

7.5 Methodology

To develop an understanding of the system sensitivities, a simulation model was developed, verified, and validated using data from several tunneling projects, including the Karaj water conveyance tunnel in Iran. The available raw data from the project site was processed. The measurements made of activity times on this project provided data about delays associated with ten (10) main tunneling activities. The data was further analyzed to prepare the time distributions presented in Table 7.1. The suitability of the best-fit functions was checked using Chi-square and least mean square error.

Table 7.1. Distributions used for the analysis (Kelton et al., 2013; Tamhane and Dunlop, 2000)

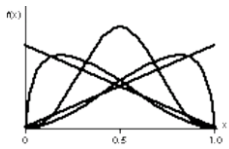
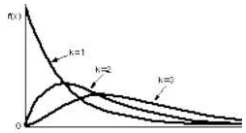
Distribution types	Distribution	Expression	Range	Mean	Variance	
 Beta	$f(x) = \begin{cases} \frac{x^{\beta-1}(1-x)^{\alpha-1}}{B(\beta,\alpha)}, & \text{for } 0 < x \cdot \\ 0, & \text{otherwise} \end{cases}$	B(β,α) B,α = Shape parameters	[0,1]	β/(β+α)	$\beta\alpha/[(\beta+\alpha)^2(\beta+\alpha+1)]$	Used to represent many input quantities that have range bounded on both ends
 Erlang	$f(x) = \begin{cases} \frac{\beta^{-k}x^{k-1}e^{-x/\beta}}{(k-1)!}, & \text{for } x > 0 \\ 0, & \text{otherwise} \end{cases}$	ERLA (ExpMean (β), k) k = Exponential random variables	[0,+∞)	kβ	$k\beta^2$	In case the activity time is integer, it is used to represent task completion time.

Table 7.1 Continued

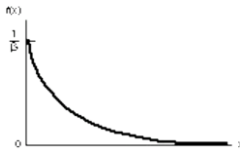
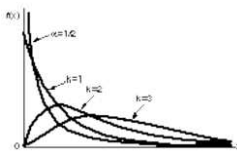
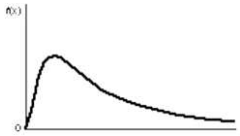
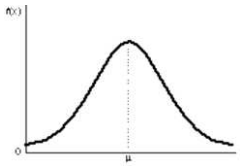
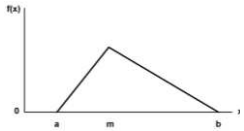
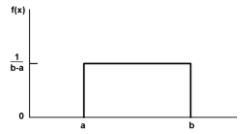
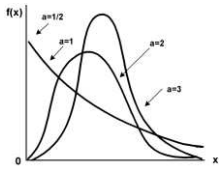
Distribution types	Distribution	Expression	Range	Mean	Variance	
 Exponential	$f(x) = \begin{cases} \frac{1}{\beta} e^{-x/\beta}, & \text{for } x > 0 \\ 0, & \text{otherwise} \end{cases}$	EXPO(Mean (β))	[0,+∞)	β	β^2	Used when determining system failure due to wear and tear
 Gamma	$f(x) = \begin{cases} \frac{\beta^{-\alpha} x^{\alpha-1} e^{-x/\beta}}{\Gamma(\alpha)}, & \text{for } x > 0 \\ 0, & \text{otherwise} \end{cases}$ Complete gamma function, Γ $\Gamma(\alpha) = \int_0^\infty t^{\alpha-1} e^{-1} dt$	GAMM(β, α) β = Scale parameter α = Shape parameter	[0,+∞)	αβ	$\alpha\beta^2$	Used in representing task completing time
 Lognormal	$f(x) = \begin{cases} \frac{1}{\sigma x\sqrt{2\pi}} e^{-(\ln(x)-\mu)^2/(2\sigma^2)}, & \text{fo} \\ 0, & \text{otherwise} \end{cases}$	LOGN(LogMean (μ), LogStd (σ))	[0,+∞)	Log mean = μ = $e^{\mu+\sigma^2/2}$	$(\text{LogStd})^2 = \sigma^2 = e^{2\mu+\sigma^2}(e^{\sigma^2}-1)$	Used to represent positive quantities like task times that are skewed to right
 Normal	$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)}$ for all re	NORM (Mean (μ), StdDev(σ))	(-∞, +∞)	μ	σ^2	It is not used for positive values like processing times.
Poisson	$f(x) = \begin{cases} \frac{e^{-\lambda}\lambda^x}{x!}, & \text{for } x\varepsilon \{0,1, \dots \dots \\ 0, & \text{otherwise} \end{cases}$	POIS (Mean(λ))	{0, 1, …… }	λ	λ	Used to represent events that occur in fixed time interval

Table 7.1 Continued

Distribution types	Distribution	Expression	Range	Mean	Variance	
 Triangular	$f(x) = \begin{cases} \frac{2(x-a)}{(m-a)(b-a)}, & \text{for } a \le x \\ \frac{2(b-x)}{(b-m)(b-a)}, & \text{for } m \le x \\ 0, & \text{otherwise} \end{cases}$	TRIA (Min(a), Mode(m), Max(b))	[a,b]	(a+m+b)/3	$(a^2+m^2+b^2-ma-ab-mb)/18$	Limited data available, only minimum, maximum and mode can be interpreted
 Uniform	$f(x) = \begin{cases} \frac{1}{(b-a)}, & \text{for } a \le x \le b \\ 0, & \text{otherwise} \end{cases}$	UNIF (Min(a), Max(b))	[a, b]	(a+b)/2	$(b-a)^2/12$	Used when no information other than range is available
 Weibull	$f(x) = \begin{cases} \alpha\beta^{-a}x^{a-1}e^{-(x/\beta)^a}, & \text{for } x \\ 0, & \text{otherwise} \end{cases}$	WEIB (β, α) β = Scale parameter α = Shape parameter	[0, +∞)	(β/α) Γ(1/α)	$(\beta^2/\alpha)\{2\Gamma(2/\alpha)-(1/\alpha)[\Gamma(1/\alpha)]^2$	It is versatile and used to represent positive task times for systems with large parts that fail independently.

The activity time distributions were set as the input parameters for the simulation model. Stochastic simulation of any construction process requires modeling the underlying random processes (AbouRizk et al., 1992) and therefore time distributions of individual activity are utilized

in this study. A flowchart was prepared for reference to the simulation model prepared in Arena© software. In total, 50 replications were performed, and the results were compared with the observed values in the real case scenario.

The simulation model showed comparable results and the outcomes were further used to assess the sensitivity of the utilization factor value to delays associated with different tunneling activities. The model sensitivity was checked for ground control issues, cutter change, maintenance, transportation, probe-drilling, utility extension, unexpected breakdown and survey delays.

7.6 Preliminary Verification of the Modeling Concept Through a Case study

The data from the Karaj Water conveyance tunnel project in Iran was used for preliminary model verification. In this study, the project is addressed as KTWCT. This nearly 30 km long tunneling project was divided into two (2) sections of 16 km (Section 1) and 15 km (Section 2) lengths. The geological details of the two sections are given in Hassanpour et al. (2014). The details of tunneling in Section 1 was considered in the analysis and section 2 was not analyzed due to limited availability of data. The lithology of this area comprises of sequence of Karaj formations which is composed of variety of pyroclastic rocks, often interbedded with sedimentary rocks. The rocks are characterized as green vitric to crystal lithic tuff, tuff breccias, sandy and silty tuffs with shale, siltstone and sandstone. The area is moderately folded and intensely faulted. The tunnel crosses wide synclines and anticlines and some thrust faults. (Hassanpour et al., 2009). The details of rock mass units are given in Table 7.2. Main issues include clay raveling in Gta1-1 and Cz, falling rock wedges in Gta1-2 and water related issues in Sts-1 Ground related issues include rock jamming, rock fallout, water inflow, cleaning muck from cutter head that were encountered in the project. Hydraulic, mechanical, electrical related delays were included in the unexpected

breakdown category. Transportation delays were also incorporated into the simulation model and included transportation and unloading of muck, train exchange, derailment, track placement and related issues. The raw database was converted to units of hours/cycle, with the cycle being defined by the stroke of the hydraulic cylinders (1.5 m) and combined into activity or delay categories. This data was transformed into time distributions and used as input in the simulation model. A total of 19 simulation models were prepared to account for the effect of tunnel distance from the excavation face to the muck disposal area located at the portal. The output from the simulations was compared with the actual site data. The simulation model predicted an average overall utilization factor of 19.8% against the actual utilization of 19.1%. The stochastic distribution of the completion time was obtained. Its mean value showed total number of days to be 984 against the actual 975 days. The details of the analysis are given in Frough et al. (2019).

7.1 Simulations and Parametric study

The sensitivity analysis was performed with the aim to identify the most critical activities affecting the utilization factor, and by extension, the performance of the machine in the project. The analysis involved first establishing the lower and upper bound for duration delay associated with each activity. This involved assessing the delay data set for each activity, identifying the smallest and largest value and varying the values in between them within +/-50% (Case I-VI). Time distributions were made with these new set of values. Ground related delays, cutter change, maintenance, surveying, unexpected breakdown and transportation system were varied individually keeping everything else constant (Table 7.3). The analysis was performed for the 10 rock mass units (Table 7.2) reoccurring along the tunnel alignment. The effect of distance and addition of train and California switch was also considered for each unit the details of which are

given in Table 7.5. In total 50 replications were executed for each scenario, and stochastic distribution of the results were recorded.

Table 7.2. Engineering geological units encountered along the KTWCT alignment (Hassanpour et al., 2010, Frough et al., 2019)

Rock mass unit	Lithology	Av. UCS (MPa)	Av. RQD	Av. RMR	RMR rating	Remarks on rock properties and descriptions
Gta1-1	Light cream lithic and vitric tuff, sandstone, siliceous tuff	55	15	35	Poor	Weak to moderately strong rock, thin to moderately bedded, fractured, may be unstable
Gta1-2	Light cream lithic and vitric tuff, sandstone, siliceous tuff	100	22	50	Fair	Moderately strong rock, thin to moderately bedded, fractured, may be unstable
Gta2	Sandstone, green vitric tuff and siliceous tuff	75	45	49	Fair	Moderately strong, thick to moderately bedded, moderately fractured, stable
Gta3	Sandstone and micro-conglomerate	100	70	64	Good	Moderately strong, thick to moderately bedded, moderately fractured, stable
Gta4	Siliceous green tuff and sandstone	150	95	75	Good	Very strong thick to moderately bedded, stable
Sts1	Massive green tuff, tuffy siltstone, sandstone and micro-conglomerate	120	60	57	Fair	Weak to moderately strong rock, thin to moderately bedded, fractured, may be unstable
Sts2	Green vitric and lithic tuff, siltstone, siliceous green tuff and sandstone	150	85	72	Good	Very strong, thick bedded, stable
Mdg	Monzodiorite, Monzogabbro	50	70	63	Good	Moderately strong, thick to moderately bedded, moderately fractured, stable
Tsh	Alteration of thin bedded shale, siltstone and sandstone	90	50	46	Fair	Weak to moderately strong rock, thin -moderately bedded, foliated, fractured, may be unstable
Cz	Crushed zone	15	15	21	Poor	Very weak strength, unstable rock

Table 7.3. Cases I-VI for sensitivity analysis

Case No.	Description
Case I	Changing Ground Condition Related Delays for Different Formations
Case II	Changing Cutter change Related Delays for Different Formations
Case III	Changing Maintenance Related Delays for Different Formations
Case IV	Changing Surveying Related Delays for Different Formations
Case V	Changing Unexpected breakdown Related Delays for Different Formations
Case VI	Changing Transportation Related Delays for Different Formations

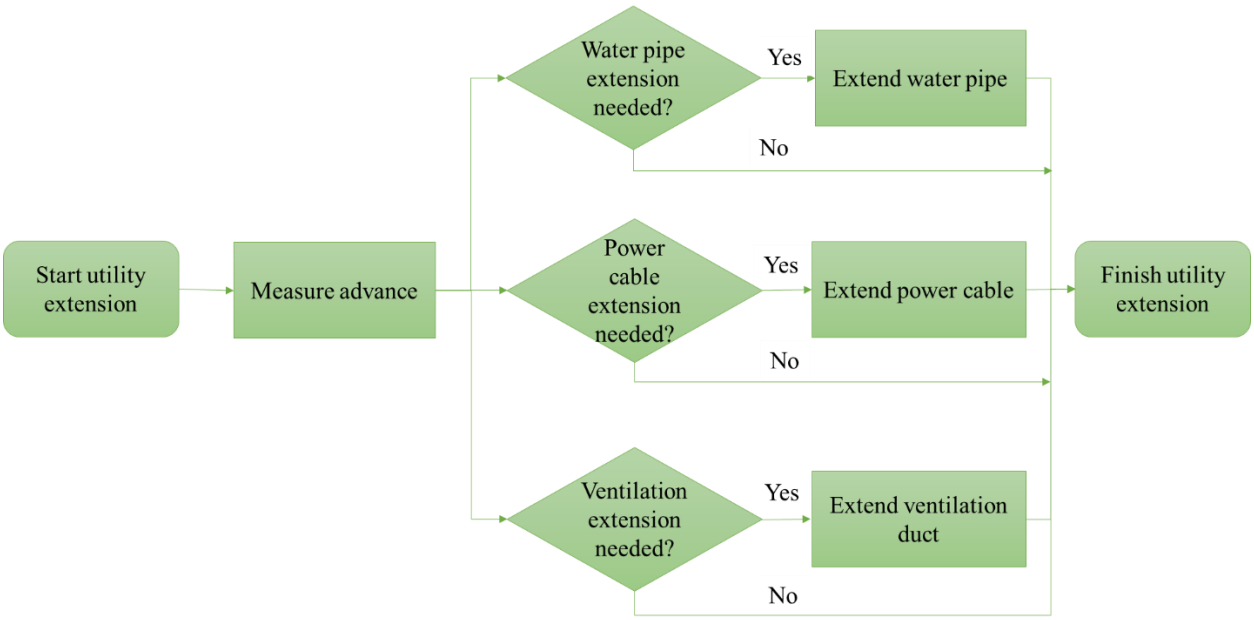


Figure 7.1. Utility extension chart

For delays associated with utility extension and probe drilling, a separate sensitivity analysis (case VII – XI) was performed as defined in Table 7.4. Two scenarios were considered for probe drilling: 100 ft. long with 10 ft overlap, and 300 ft. long with 30 ft of overlap. The average delays were established associated with extension of the ventilation line (1.0 hr), power cable (3.5 hr), and water drainage pipe (1.0 hr). The flowchart for the utility extension analysis is shown in Figure 7.1.

Table 7.4. Cases VII-XI for sensitivity analysis

Case No.	Ventilation extension	Power cable extension	Drainage pipe extension	Probe drilling
Case VII	Every 160 ft	Every 160 ft	Every 160 ft	-
Case VIII	Every 300 ft	Every 300 ft	Every 300 ft	-
Case IX	Every 650 ft	Every 1000 ft	Every 300 ft	-
Case X	Every 650 ft	Every 1000 ft	Every 300 ft	Every 100 ft with 10 ft overlap
Case XI	Every 650 ft	Every 1000 ft	Every 300 ft	Every 300 ft with 30 ft overlap

Table 7.5. Details of occurrence along the tunnel alignment of the 10 rock mass units with number of trains and California switch activated in that length

Rock mass units	RMR	Distance from the portal Station (m)		Length (m)	No. of trains	Number of activated California switches
		From	To			
gta1-1	35	163.27	208.82	45.55	1	0
cz	21	208.82	247.67	38.85	1	0
gta1-2	50	247.67	2429.65	2181.98	2	1
cz	21	2429.65	2458.73	29.08	2	1
gta1-2	50	2458.73	2767.55	308.82	2	1
gta2	49	2767.55	4756.23	347.31	2	1
gta-3	64	4756.23	6274.75	188.55	2	2
sts-1	57	6274.75	6622.06	288.6	2	2
sts-2	72	6622.06	6913.3	1070.26	2	2
gta-3	64	6913.3	7101.85	2261.7	3	2
sts-1	57	7101.85	8002.67	598.48	4	3
sts-2	72	8002.67	8291.27	442.32	4	3
sts-1	57	8291.27	8921.72	630.45	4	3
gta-2	49	8921.72	9991.98	1070.26	4	3
sts-2	72	9991.98	10751.07	759.09	4	3
gta-4	75	10751.07	12000	1248.93	4	3
gta-4	75	12000	14264.7	2264.7	4	3
sts2	72	14264.7	14683.42	418.72	4	3
tsh	46	14683.42	15281.9	598.48	4	3
mdg	63	15281.9	15724.22	442.32	4	3

7.2 Summary of the Results

The average value obtained from the stochastic distribution is presented in the spider graphs in Figure 7.2. The overall results show that, in general, the utilization factor value decreased with increase in delays, as anticipated, however at non-uniform rate. Maintenance related delays showed maximum impact on utilization factor with a reduction in the range of 6%. The impact of other delays was limited to around 3% reduction in utilization, with the exception of excavation in one geotechnical unit (gta1-1) which experienced more extensive ground related delays. In this tunnel section many of the activities were covered and could be done parallel to ground support and the related downtimes were not an issue and thus did not impact TBM utilization. In other words, the model can show the anticipated sensitivity or impact of certain activities (or lack of it) and related features on the machine or in the backup system on machine utilization. This could also be dependent upon the location of the geological feature along the tunnel.

The pie chart for distribution of downtime for the Karaj tunnel project has been presented in a previous study (Khetwal et al., 2019), and the related analysis shows that maintenance delays contributed 19% towards total downtime. In present study, the maximum sensitivity was observed in "fair" quality rock masses (RMR between 41 and 60) where machine performance is near optimum and highest regarding the speed of excavation and low requirement for ground support. This means that in favorable ground conditions for TBM operation, maintenance delays are the most critical parameter in determining TBM utilization factor. For two of the geotechnical units (cz and gta1-1), no sensitivity to machine related activities was observed, as the majority of downtimes were due to ground related delays, thereby overshadowing all other downtime sources.

Sensitivity analysis due to cutter change shows similar trend as maintenance. However, the percentage difference lies within ~2%. Transportation delays were most strongly affected by the

activation of California switch. As per Table 7.5, for initial 45.55 m, only one train was active and therefore it shows maximum decrease of ~4% in U value. However, it can be seen that at 5,000 m from portal, maximum gain in the U value of ~3% was obtained as both the decrease in delay and presence of optimum number of California switches (2 numbers) optimized the transportation system.

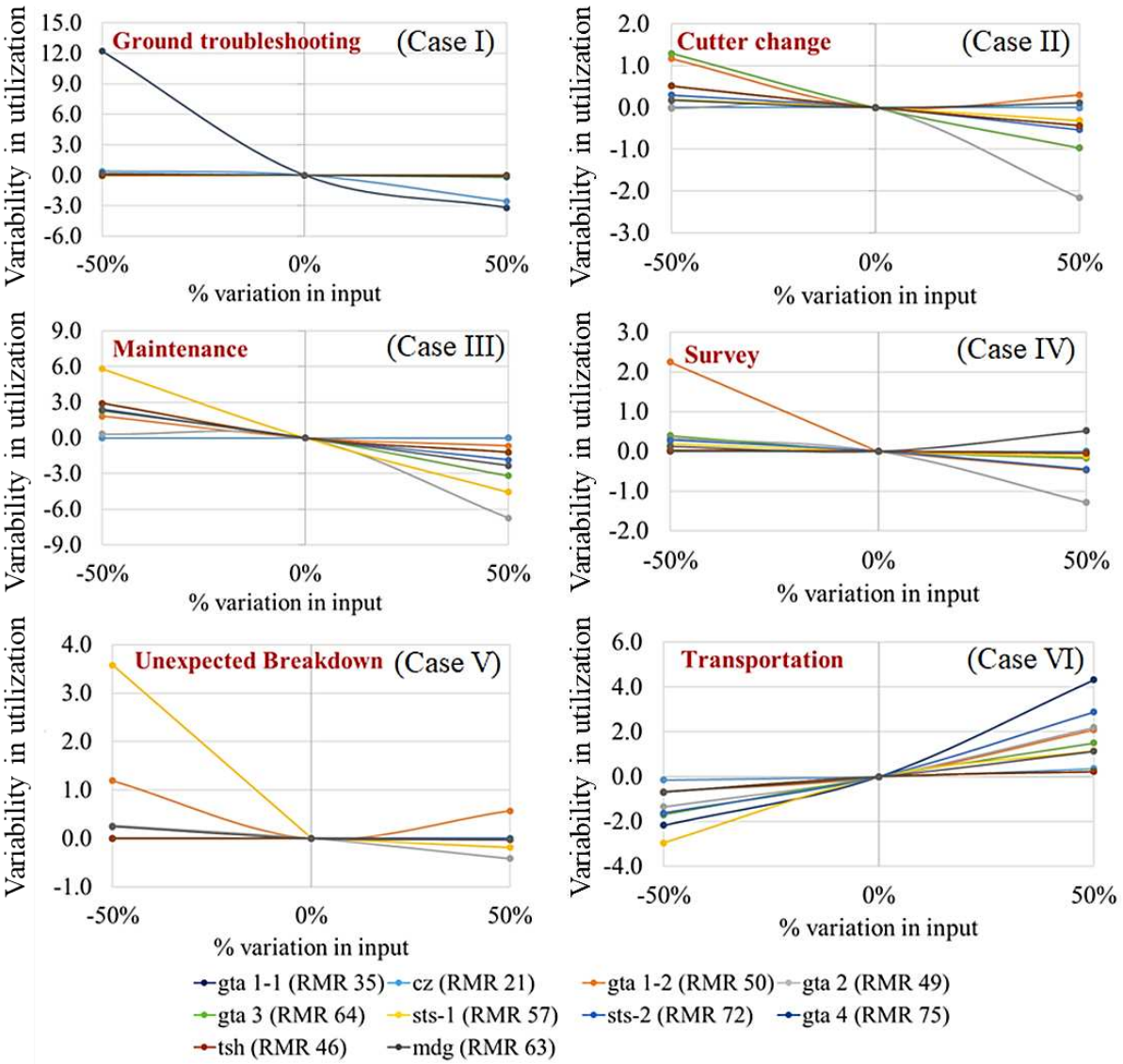


Figure 7.2. Sensitivity analysis of cutter change, transportation, survey, ground troubleshooting, maintenance and unexpected breakdown delays

Analyzing the results of system response to survey and unexpected breakdown delays showed the maximum sensitivity in U value in fair to good rocks as well. However, it is observed that by increasing the delays, slight gain of order of ~0.5% in U value can be observed. This may be attributed to the fact that unexpected breakdown includes hydraulic, mechanical, electrical, lack of materials, and some unknown issues can affect the operation and therefore utilization.

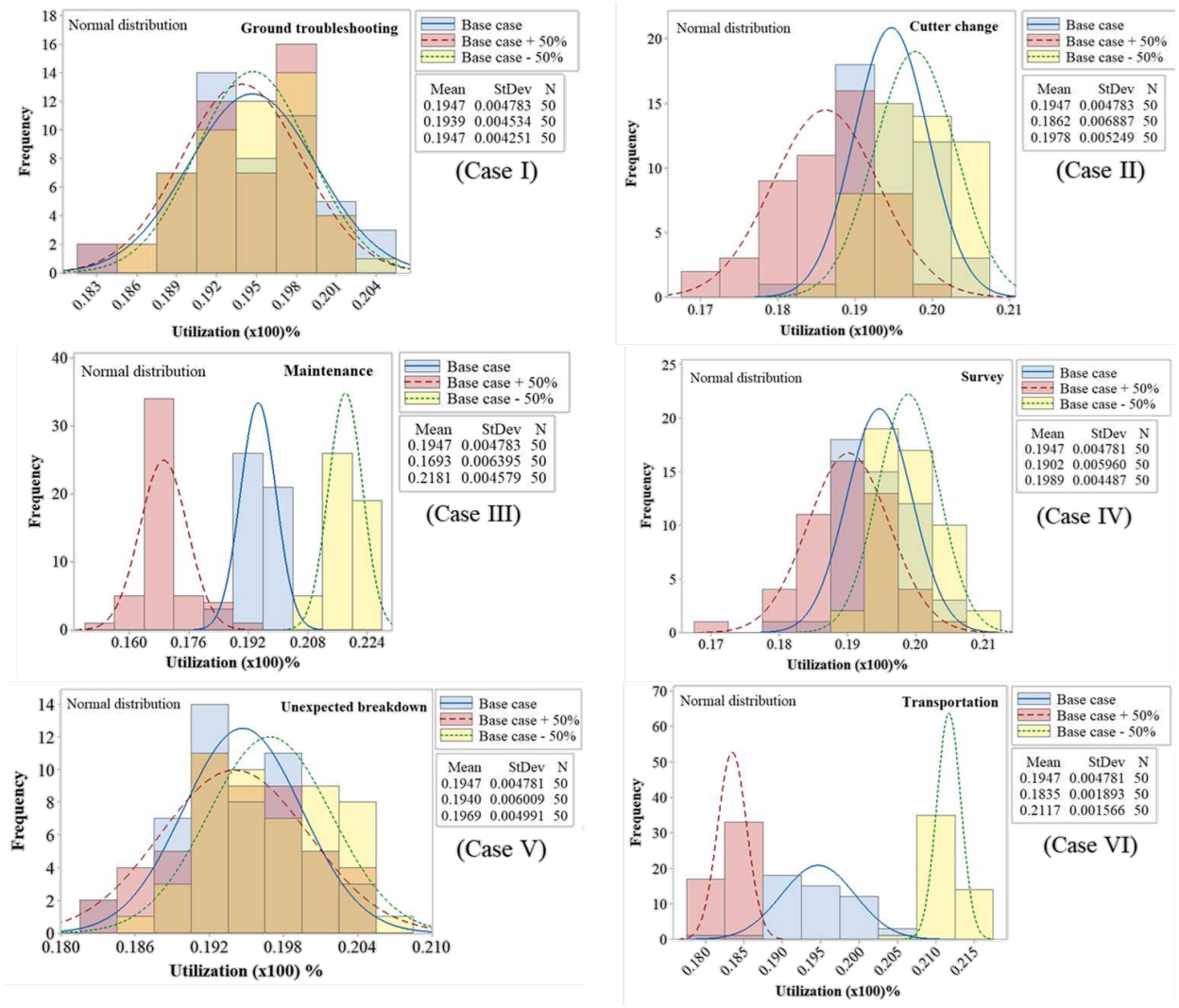


Figure 7.3. Stochastic distribution for Case I-VI

The detailed results of the stochastic distribution obtained for the cases I-VI (Table 7.3) are shown in Figure 7.3.

Analyzing the sensitivity of the TBM performance to ground related delays, 12% increase in the U value is noted for RMR 35 indicating the geology-related delays to be the major bottleneck for this tunnel section. Cz unit (RMR 21) showed increase of 0.5% only indicating that even if reducing the ground related delay by 50% was possible, a significant amount of delays is detected due to various other tunneling activities. The ground in this section is described as very weak, unstable rock with clay and dripping to flowing groundwater (Frough et al., 2013). The decrease in U by 3% was observed for RMR 21 and 35 when the delay was increased.

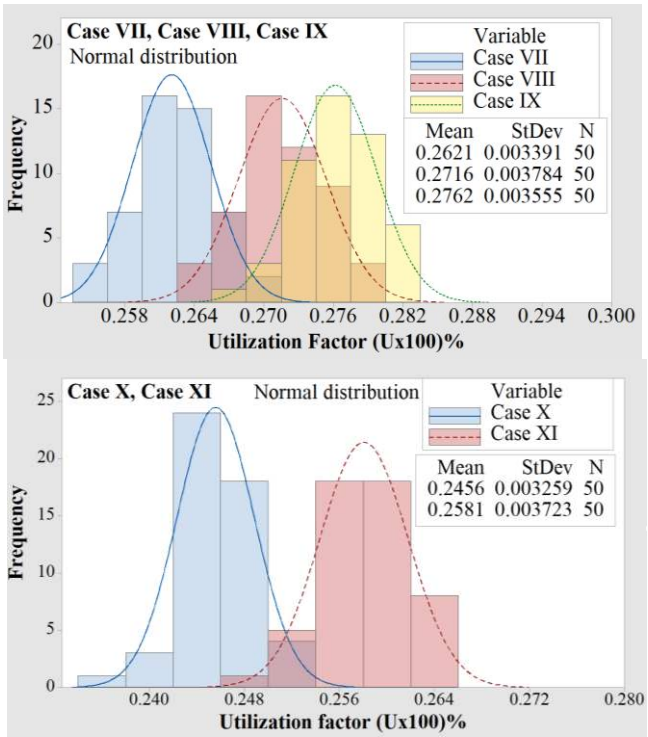


Figure 7.4. Estimation of utilization factor with change in utility extension and probe drilling

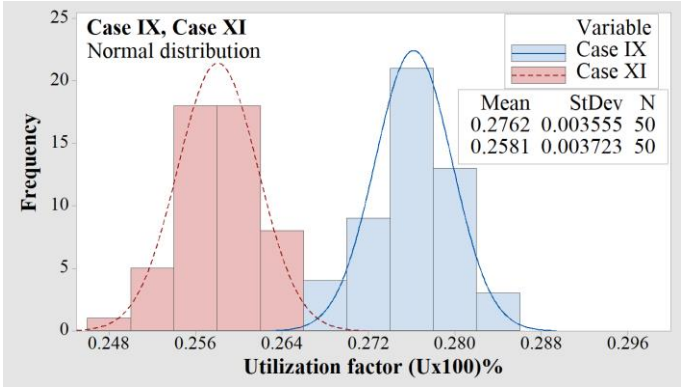


Figure 7.5. Variation of utilization factor for Case IX and X, for simulating the effect of addition of probe drilling

Further assessment of U by varying utility extension and probe drilling was done by analyzing the cases VII-XI as given in Table 7.4. When comparing the best and worst case scenarios (Case VII with Case IX and Case X and Case XI, see Figure 7.5), difference of 2% in the overall utilization factor can be realized. These results suggest that optimizing individual tunneling activities in certain settings can lead to notable increase in the performance of the machine. However, comparing Case IX with X, the change in the utilization is 3.5% suggesting that the gain in the utilization due to utility extension optimization is masked by the delays due to probe drilling for the 2000 m (6500 ft) of tunnel excavation. This result may be attributed to time delays and frequency of occurrence of these activities during the tunneling operation. The calculation, however, do not recommend avoiding probe drilling, instead shows that the delays due to this activity must be considered for utilization estimation. The results can be used by the contractors and machine manufactures to do a tradeoff study for selection of the best range for utility extensions and probe drilling, especially in the case of smaller TBMs, where the available space for storage of power cable, water drainage hose, ventilation carrousels, etc. is limited and can cause major design issues for the back-up system. Therefore, the best combination of utility

extension that can allow for higher machine utilization can be identified and used for the design of the subsystems. This concept can be extended to the design of the tunnel haulage system, location of California switches, and other machine and back-up components.

7.3 Conclusion

This paper is focused on understanding the significance of different activities, especially those related to management of site excavation systems and its logistics, on the performance of the TBM in completion of a tunneling project and efficiency of the overall system. The DES approach has proven to be capable of analyzing the complex tunneling operation wherein individual tunneling activities can be taken into consideration. In this study the impacts of ground support, cutter change, maintenance, transportation, probe-drilling, utility extension, unexpected breakdown, and survey delays on TBM utilization were examined. The critical activity and the redundancy in the extra time to be allocated to certain component or activity can be identified/quantified through this analysis. The following is a brief summary of the findings from this study:

- The system utilization while excavating in geotechnical units with lower RMR values (21 and 35) showed very low sensitivity to machine related downtimes, because major delays were caused by the ground-related issues and therefore time required for ground stabilization overshadowed the delays due to other activities. In fair to good ground (RMR between 45 and 75), the ground-related delays are not significant and therefore logistic management is the key to controlling the utilization factor.
- In ground with RMR between 45 and 75, maintenance delays showed maximum impact with 6% variation in utilization factor. The analysis however indicated that the U value was not very sensitive to cutter change. Transportation delays including activation of California switch were

the crucial factor. Unexpected breakdowns, on the other hand, comprising of many other activities like hydraulic, mechanical, electrical problems, non-availability of materials, TBM conveyor issues did not show any general trend with variation in the utilization.

- The Utilization impact from utility extension delays showed a similar trend to that for cutter change. However, the data was not divided between the types of extensions (as per Figure 7.1.) and therefore, clear identification of its type cannot be determined in this analysis.
- Probe drilling impacted machine utilization. The analysis showed an increase of 2% in Utilization was possible by changing to longer probe holes, and a Utilization increase of 4% when the probe hole drilling was removed from the operation. This utilization increase must be weighed against the possible gains by conducting probe drilling and potential ground conditions issues that can be averted.

Overall, this study shows the potential of stochastic DES modeling to represent the overall construction operation when using a TBM for tunneling. This method of analysis offers a powerful tool for objective selection of machine type and subsystems, as well as site planning. DES simulation offers the ability to evaluate the impact of various subsystems in increasing overall machine utilization in a given geological setting and site related constraints. Additional efforts are underway to expand the available models to other machine types and evaluate the input parameters towards development of a full predictive model for machine utilization.

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CHAPTER 8

INTRODUCING A DATA COLLECTION/ PROSSESSING SYSTEM FOR COMPILATION OF TBM FIELD PERFORMANCE DATA

8.1 Abstract

The accurate estimation of machine utilization depends on the data set used and no such uniform data collection technique is available for this. The present study aims at identifying the tunneling activities that affect the utilization estimation and proposing a uniform technique for collecting the required information. The detail of data available for seven projects have been identified and a template is proposed combining them. A visual basic for application (VBA)-based user interface has been developed that can incorporate the data from available reports before construction and can be applied to future estimation of utilization for other future projects. Keywords: TBM, utilization factor, data collection framework, discrete event simulation

8.2 Introduction and background

The growing need of tunnels in the present world demands an efficient methodology for construction. This requires resourceful management of the various site logistics including operation of tunnel boring machine (TBM) systems which include the TBM itself and the backup system behind it that is required for its operation. The backup system includes mucking, transportation, utility extension (water pipes, electric cables, ventilation ducts), and surveying guidance systems, among others. Management of these TBM logistics determines the overall performance of machine, and ultimately affects the project completion time. However, back-up systems differ from each other considering the TBM design, project requirements and contractor's experience. For example, the muck conveyance system may either be via train with muck cars or

conveyor belt. Similarly, variation in other systems occur, so it is necessary to incorporate these differences in developing a methodology to estimate the performance of the whole TBM system. Any variation in terms of time allocated to perform each activity is important for performance prediction and decision-making and therefore, a flexible database management system is paramount considering the intention for long-term applicability and reference for future projects.

The various available TBM system performance prediction models are based on analysis of huge database. For example, the Norwegian University of Science and Technology or NTNU model by Bruland (1998) later updated by Macias (2016) is based on site studies and statistics obtained from more than 40 tunneling projects in Norway and abroad having more than 300 km of tunnel (Macias, 2016) while the Rock Mass Excavability (RME) is based on 400 tunnel sections (Bieniawski et al., 2007), and QTBM methodology is based on 145 tunnel projects with combined length of more than 1000 km (Barton, 2009). A set of prediction equations provided by Farrokh (2012) is based on data obtained from 300 projects from to past three decades with detailed data for 17 recent tunnel projects, whereas Laughton (1998) used data from over 640 TBM case histories having clear identification of tunnel layout, rock types and TBM performance for the whole tunnel length. These approaches were taken with recognition of the need to encompass the heterogeneity in the time allocation for different activities. As pointed out by Duhme (2016), the shift reports prepared for keeping track of the major events during construction are often filed on paper and forgotten which makes it difficult to use for future reference. Hence, there is a need to have a standard electronic system that can help in estimating the time to perform certain predefined set of activities and estimate component and aggregate downtimes for any project.

The growing need for tunnels in the present world mandates efficient and safe construction methods, and tunnel boring machine (TBM) systems are increasingly the method of choice for

tunneling. Efficient operation of TBMs involves resourceful management of the various site logistics including operation of TBM machine and the whole backup system from the tunnel face to the portal/shaft entry and including surface facilities. Management of these TBM system logistics affects the overall performance of machine, and ultimately determines the project completion time. However, there are subtle differences between back-up system offered by TBM manufacturers based on their preferences, project requirements, contractor's experience, and site-specific constraints.

8.3 Data acquisition

Appropriate application of data and data analytics can assess the project experience, identify total knowledge gained in the project, and serve as a communication and information platform for all stakeholders. The necessity of data management is paramount as it serves as a foundation in decision making process. Typical field performance and operational data for TBM is stored in a condensed format due to reasons related to volume and understandability. However, the process of data condensation and interpretation must be transparent to identify possible biases. If the data originates from different sources, it is necessary to standardize the data structure. Various data collection and database management methodologies have been proposed for construction projects. A database for 386 tunnel projects undertaken by the Robbins Company between 1952 and 1990 was collected by Howarth (1994). The paper, however, did not propose a standardization of format and level of data detail, nor a methodology for database management. Costin et al. (2012) identified the issue of human error in data collection that can hamper the accuracy of data analysis required for future decision-making processes.

A web-based data management system was developed for the Alp transit Lotschberg and Gotthard base tunnel in Switzerland known as SISO (Site Information Software). The SISO project

proposed controlled sharing of information related to real-time progress of tunnel construction, project reports, letters and other information that allowed for clear communication between the client, consultant and contractor that led to informed decision-making processes, achieving deadlines and controlling the cost. The software was further used for the Brenner base tunnel in Austria, the Ceneri base tunnel in Switzerland, and the T-48 railway tunnel project in India among others (e.g., Neuenschwander et al. 2006, and Khetwal et al. 2017).

Javed et al. (2020) developed a data acquisition system for small spherical Tokamak with an insulated vacuum vessel of Pyrex using Labview and MATLAB software. Sugimoto and Nishida (2015) and Sagimoto et al. (2010) proposed a data collection methodology for shield tunnelling for which the database would be divided into tunnel basic info, documents and site monitoring data. Pejic (2013) suggested that an approach of data collection and analysis in terms of drawings and numerical reports for the tunnel survey using laser technology to inspect railway tunnels would have better data representation. Li and Zhu (2013) proposed a web-based shield tunnel construction data model using unified modeling language (UML). Yin et al. (2020) proposed a building information modelling framework for an operation and maintenance management system that provided cost, contract, equipment, safety and other relevant information for utility tunnel construction. However, the framework did not include other critical issues such as hydrology, geology and geotechnology that have a strong impact on efficient development of operation and maintenance strategies.

Database design for tracking the rock mass data during tunneling was proposed by Decker et al. (2006) wherein the real time data collection in terms of images, laboratory results, field monitoring, geological field data and tomography was fed in to a centralized project data base that was further used for preparing reports, optimizing designs and as input for numerical, stochastic

and virtual environment models. Costin et al. (2012) used a concept of implementation of a radio frequency identification (RFID) tool to assess the movement of laborers along with the cycle time of the hoist for a construction of high-rise structure. The concept of automated data collection technology helped in understanding the delays associated with material supply, thereby optimizing the performance for that aspect of the tunnel system operation. Ding et al. (2013) discussed the use of RFID in the cross-passage construction, using RFID tags to the laborer, record their position and ensure safety with the data fed into a real-time safety early warning system. Such a concept could be used to monitor tunnel construction activities like determining the position of a train system that conveys muck and supplies.

Abd Al-Jalil (1998) proposed a four-level database based on available details from a tunneling project. In level-1, average performance for a whole tunnel project with general description of geology was known. For level-2, the alignment and performance were subdivided into geotechnical units or zones. If further elaboration of data in terms of shift reports for each ground class were known, the project was included in the level-3 database, and if full detail of ground class and performance of the TBM per stroke was known the project was included in the level-4 database. A Delphi method was used to estimate the time required to perform certain tunneling activities whose time allocation was unknown. This approach incorporated the expert knowledge through interviews into the database wherein a set of questionnaires were sent to group of experts and their responses were gathered and shared within the group after which the experts can adjust the answers and a true consensus was obtained which was then included in the system.

8.4 Data acquisition and analysis for different performance prediction models

Successful planning of any construction project with further enhancements can be achieved using a simulation approach (Touran and Asai, 1987; AbouRizk et al., 1999; Rawanpura and

Ariaratnam, 2007). Simulation models are opportunistic tools that allow the exploration of "what-if" scenarios (AbouRizk, 2010; Al-Bataineh, 2012). Contributions in terms of comparison of alternatives for project selection, planning, scheduling and estimating and construction planning are made using simulation approach (Rawanpura and Ariaratnam, 2007). Sawhney (1997) used the perti net based scheduling technique to simulate the dynamic aspect of construction project. Shi (1999) and Martinez (2001) proposed an activity-based construction (ABC) modeling and simulation to account for dynamic and random behaviors and construction processes that are considered as a limitation for critical path method. Copur et al. (2014) analyzed a stochastic model using Monte Carlo simulation to predict the machine utilization time using linear cutting test data. Liu et al. (2014) studied the Jingping hydraulic tunnel in China to predict the performance of a TBM using cyclic operation network simulation and found a high risk of delays due to ground issues. They suggested the possible implementation of ground-related uncertainties in the simulation model. The interaction between the TBM and ground was found to be the key factor by Maidl and Stascheit (2014) using computer-based data management system for optimization of the tunneling process. Extensive data collection and analysis was performed to set a base for comparing the various performance prediction models as suitable data reference marks the cornerstone for accuracy in estimation. The data available for analysis involved interpretation of the type and condition of equipment in use, handling skills, local conditions and its interactions with other processes. As pointed out by Duhme (2016), a key challenge is determining the interdependencies among different activities and how these interdependencies should be reflected in the data acquisition system. Therefore, understanding the sensitivity of parameters is the initial step in introducing data acquisition system.

Khetwal et al. (2019) performed sensitivity analyses to identify the impacts on TBM utilization due to TBM disc cutter changes, maintenance and transportation system delays with reference to change in ground conditions along the tunnel alignment for the Karaj water conveyance tunnel project in Iran. The criticality of these activities in determining the performance of machine was identified. The study showed that while maintenance plays a vital role in utilization estimation, the transportation system is more dependent on the tunnel length and number of California switches. In higher Rock Mass Rating (RMR) value rock masses, the schedule and delays associated with cutter changes needed to be optimized to increase the performance of the machine. Khetwal et al. (2020a) performed detailed sensitivity analyses by varying the delay time for various tunneling activities, and this work demonstrated and quantified the importance of detailed data collection.

Farrokh (2012) categorized TBM project data on the excavation system performance and ground type and considered the level of detailing available for several projects. A set of parameters was identified, and the database was divided accordingly. While his general data base included some preliminary time allocation details for tunneling activities, a detail database was possible to establish for 17 projects that had specific time allocations available for most of the activities. These were used to fine-tune the proposed regression equations to predict the time allocated for different tunneling activities for input into TBM system utilization estimation.

The data used in work with the NTNU model by Macias (2016) came from current projects and experience accumulated during the last decade. The details included the geological data from engineering geological back-mapping and drillability testing, machine specifications and TBM data. The machine parameter details were obtained from the logger system which is often installed in modern TBMs. Parameters include excavation duration (cutterhead rotating), gross thrust,

cutterhead velocity (rpm) and the position on the cutterhead and rolling distance life for changed cutters. Raw data from shift logs by TBM crews were also analyzed. Cutter consumption details were obtained from the cutter repair logs and shift reports.

The Rock Mass Excavability (RME) index by Bieniawski (2007) uses detailed data on rock mass characteristics and TBM parameters that are depicted in the RME input data form. These include details of the rock mass characteristics, uniaxial compressive strength, drilling rate index, type and variability of the lithology at the excavation face, number of joints per meter, RMR range, orientation of discontinuities, stand up time and groundwater inflow. The TBM parameters details included average speed of cutterhead rotation, thrust, penetration rate, number of cutters changed and TBM system excavation days, advance rate, and utilization. Project data included tunnel length and average depth.

As an alternative, a performance prediction model using discrete event simulation (DES) has been proposed by Frough et al. (2019) using Arena© simulation software. The results of DES simulation model were compared with the actual values observed in the case studies. The results of modeling and simulation for estimation of U were initially verified using data from Karaj water conveyance tunnel project, lot 1. The lithology of this area consists of variety of pyroclastic rocks that are interbedded with sedimentary rocks, mainly green vitric to crystal lithic tuff, tuff breccias, sandy and silty tuffs with shale, siltstone and sandstone (Hassanpour et al., 2009). Ground related issues were rock jamming, rock fallout, water inflow and, cleaning muck from cutter head. Hydraulic, mechanical and electrical related delays were collectively considered as the unexpected breakdown. Transportation delays comprised of delays in loading and unloading of muck, train exchange, derailment, track placement and related issues. The raw database obtained from site was converted to units of hours/cycle and time distributions were made from them, where the cycle is

the stroke of the hydraulic cylinders (1.5 m). These time distributions were fed into the simulation model as activities and delays. A total of 19 simulation models were prepared to account for the effect of tunnel distance from the excavation face to the muck disposal area located at the portal area and addition of California switches with increasing length. The simulation model predicted stochastic distribution of utilization with an average value of 19.8% against the actual utilization of 19.1%. The model was further used to compare the utilization of Nowsood project and average utilization of 13.3 % was observed against the actual 15.3%. Hence, DES approach proved to be a promising method for U estimation. This approach is not based on any specific data collection but provides a platform for utilization estimation wherein the various tunneling activities can be set as input and their interrelationship can be incorporated through different dedicated modules that are site specific. This adaptation is discussed in Khetwal et al. (2020b).

Hence, it can be seen that the methodology adopted for different performance prediction models vary considerably and therefore adopting a common platform for data acquisition will encourage to address the missing aspects in the existing models and comparison between them can be made that is useful for understanding the accuracy of these models. The existing approaches are incomplete in terms of the types of data/information recorded, so are difficult to compare consistently. Regardless of the approaches, a complete standard terminology for time and activity/materials analysis on tunnel projects is one of the most fundamental needs for U estimation. For proposing a methodology for data acquisition and database management, some critical points must be addressed like the usability of data, level of detailing required in the data collection, the careful interpretation of data to avoid biases and acknowledging the gaps in the available data. The present study aims at establishing a two-phase database that can be used for the estimation of TBM utilization. The input data obtained from various sources influence the

tunneling activities that ultimately affects the utilization of the machine. The details of activities sensitive to the input parameters are given in Figure 8.1.

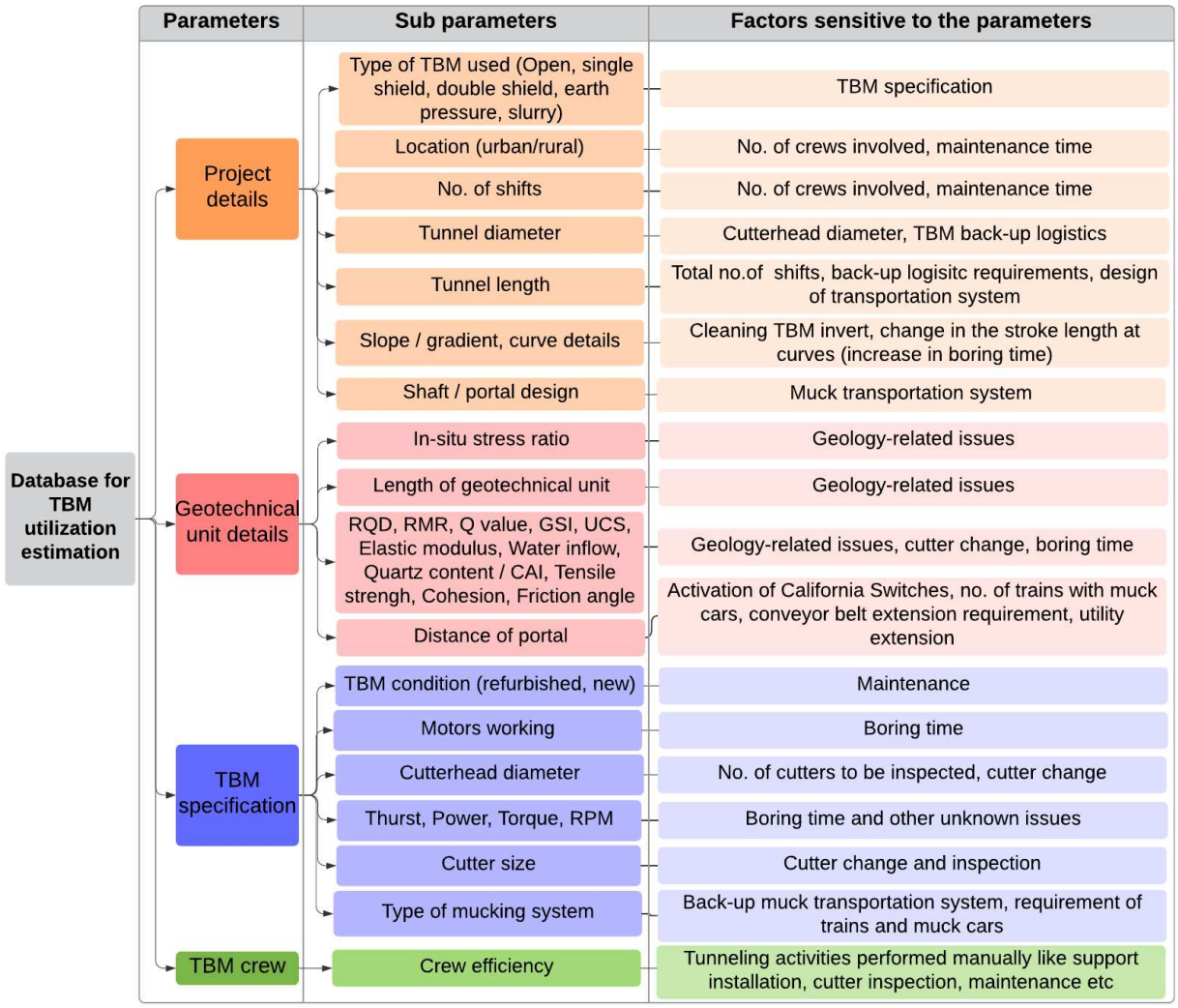


Figure 8.1. Interpretation of parameters affecting tunneling activities

8.5 Methodology

Data acquisition is mandatory to assess uncertainty risk for tunnel projects, and to decide whether experience at one project may be appropriately extrapolated for performance prediction of a new project. For such applications, the importance of establishing a systematic methodology

for data collection is clear. In this present study, a common tool of visual basic for applications (VBA) in MS Excel is used, and the tool is developed initially considering a hard rock tunnel boring machine project. The input data is divided into deterministic and probabilistic sets taking reference from Abd-Al Jalil (1998). The deterministic data include values like the stroke length, speed of conveyor belt, average speed of train and length of each geotechnical unit or zone. Other activities like boring time, ground troubleshooting, surveying, maintenance, cutter change, utility extension, probe drilling, segment installation and regrip, muck dumping time, electrical, mechanical and hydraulic issues, and unexpected breakdowns are based on the time required to perform these activities , and are treated as probabilistic data that is sampled from distributions obtained from study of previous projects.

For the purpose of data gathering, the source from which data can be obtained should be made clear. Duhme (2016) listed a set of resources for data acquisition that includes video/ audio recordings, jobsite personnel interviews, automatic sensor recordings, manual stopwatch recordings, activity duration database, sensor data recordings and specification sheets. These sources are site specific and not all methods are available for data collection on every project. Considering the commonly available sources, the data is divided into four major groupings as shown in Figure 8.2. The data related to TBM operations can be obtained from the specification report and sensors installed at the cutterhead, while general project details can be obtained from sources such as the baseline reports. Historical reports can be obtained that are related to similar nearby projects to better anticipate possible site conditions. The time allocated for each tunneling activity can be obtained from the daily shift reports and from the TBM operator reports, and such data can be compared with the equipment-specific technical sheets to assess actual operation versus system or equipment design capacity. Personnel interviews help in understanding the

possible delays or change of operation or ground conditions that are critical for utilization estimation. Manual recordings sometimes performed by engineers at site also deliver details that are logistic-specific like making time lapse records of the muck transportation system and possible downtimes related to derailment or other issues. Since current typical data acquisition systems aim to determine the machine utilization, the interpretation of penetration rate is not included in this format. However, the data can very well be used for the estimation of penetration rate.

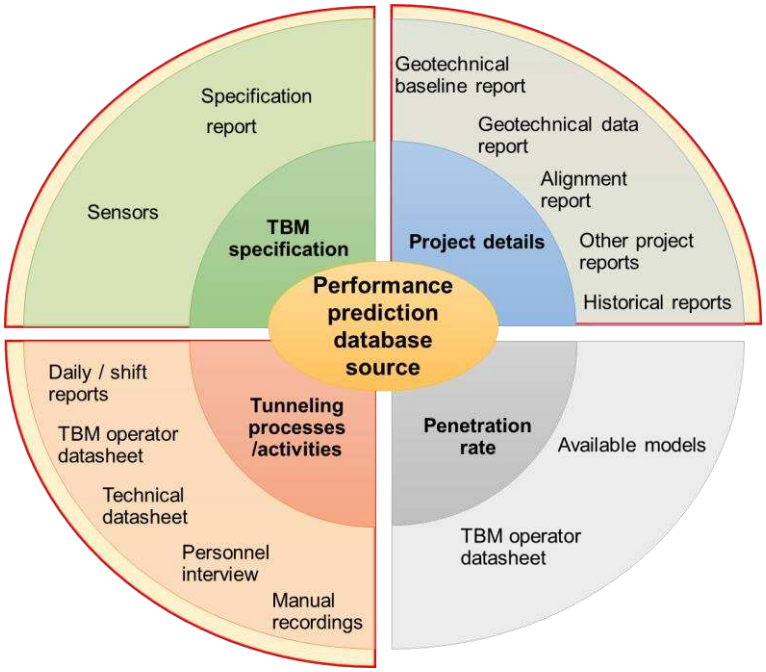


Figure 8.2. Source for database for performance prediction. Red boundary represents the documents used for utilization estimation

For this project, the data management system was divided into two phases. The three modules shown in Figure 8.3 are first phase input, processes and output. The first phase module include data that is obtained from the available reports that are prepared during the design phase. The entities in this module are TBM specification, project specification, geotechnical unit details and penetration rate. The project specification includes the data that are obtained from the design

report while the TBM specification entity includes attributes that are obtained the report generated by the TBM manufacturing company. The geotechnical unit details include attributes related to geotechnical aspects of the project that give an idea of the possible ground-related issues. The penetration rate is calculated using the information from various documents as shown in Figure 8.2 and is directly set as input for the advance rate calculation. The second phase module is called "processes" that include entities related to different tunneling activities that are performed mainly during construction. The entities in this module are routine maintenance, electrical, hydraulic, mechanical issues, utility extension, regular check of equipment and TBM parts, excavation and segment installation, ground troubleshooting, transportation issues, unexpected breakdowns, failure of equipment and crew experience. These entities directly affect the machine utilization and is fed into the simulation model for the performance prediction estimation. The second phase data is divided into three types on the basis of project stage at which the analysis is performed i.e. before construction, during construction and after construction. For the before construction project stage, the database available from other similar historical projects can be used as input while during construction, direct input from the daily report and TBM operator sheet can be used. For determining the utilization after construction, the data obtained from the daily reports and operator sheets can be set as input which can further be analyzed, and a comparison can be made. The third module is "output" which gives the machine utilization and advance rate values that are estimated from data obtained from the other two modules.

After collection of the data in the second phase, it was modified into hour/cycle (cycle is the stroke length) for each tunneling activity and their best-fitting curve was obtained that is set as input in the discrete event simulation model for the estimation of machine utilization. This best-

fitting curve is obtained using MATLAB code. The goodness of fit for the curve was checked using Kolmogorov and Chi-square methods. The application of each distribution was given in Khetwal et al. (2020) and therefore the distributions were selected on basis of their applicability and response at the tails.

As per Kelton et al. (2013), the gamma distribution can be used to represent the time required to complete a task which are tunneling activities in the present study. Further, the distribution is very adaptive and can take any form as its shape parameters change as shown in Table 8.1. . Triangular distribution on the other hand can be used when the exact form of distribution is not known and only the estimates for minimum, maximum and most likely values are known. In the present study, the activities whose data was very limited or not available, this distribution was set as input into the simulation model.

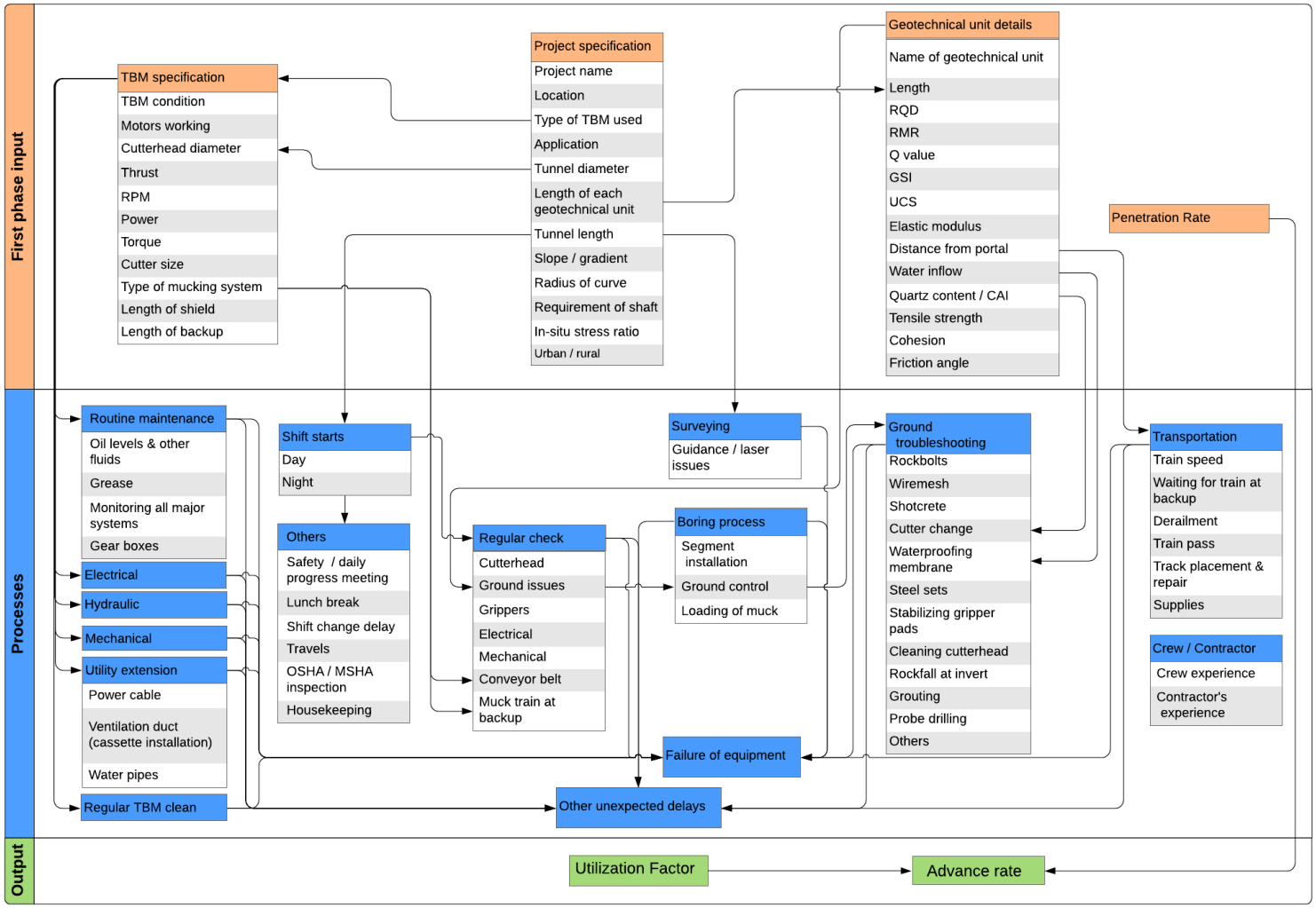


Figure 8.3 Database input and their interrelationship for the utilization estimation

Table 8.1. Distributions used for the analysis (Kelton et al., 2013; Tamhane and Dunlop, 2000)

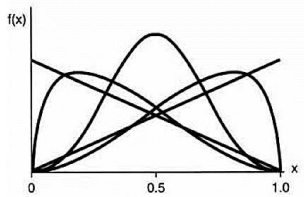
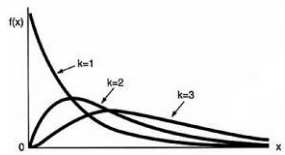
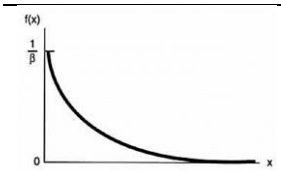
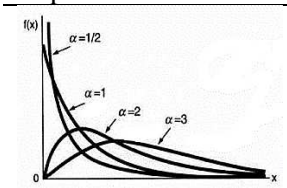
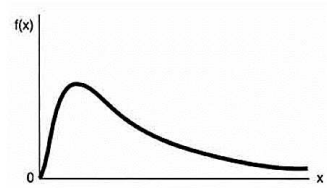
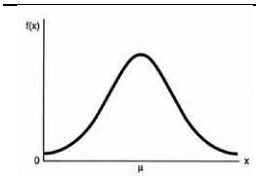
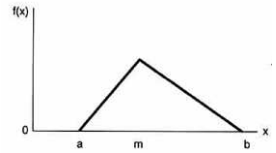
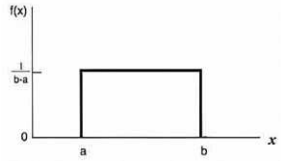
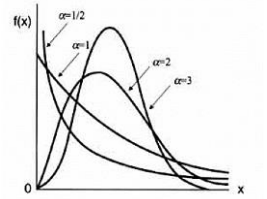
Distribution types	Expression	Range	Applicability
 Beta	B(β,α) B,α = Shape parameters	[0,1]	Range limits its applicability for tunneling activities as the time allocation can be more than 1 hour
 Erlang	ERLA (ExpMean (β), k) k = Exponential random variables	[0,+∞)	In case the activity time is integer, it is used to represent task completion time. Since the time allocation is given in hours, integer values are not fully representative
 Exponential	EXPO(Mean (β))	[0,+∞)	Inappropriate for modeling process delay times
 Gamma	GAMM(β, α) β = Scale parameter α = Shape parameter	[0,+∞)	Used in representing task completing time
 Lognormal	LOGN(LogMean (μ), LogStd (σ))	[0,+∞)	Used to represent positive quantities like task times that are skewed to right. Can give very large processing time and can cause misrepresentation
 Normal	NORM (Mean (μ), StdDev(σ))	(-∞, +∞)	It is not used for positive values like processing times.

Table 8.1 Continued

Distribution types	Expression	Range	Applicability
Poisson	POIS (Mean(λ))	{0, 1, ……}	Used to represent events that occur in fixed time interval. Is not appropriate for time allocation of tunneling activities.
 Triangular	TRIA (Min(a), Mode(m), Max(b))	[a,b]	Limited data available, only minimum, maximum and mode can be interpreted
 Uniform	UNIF (Min(a), Max(b))	[a, b]	Used when no information other than range is available
 Weibull	WEIB (β, α) β = Scale parameter α = Shape parameter	[0, +∞)	It is versatile and used to represent positive task times for systems with large parts that fail independently.

The details of TBM and its back-up area provides input like the number of cutters and their positions that is required for estimating the approximate time for cutter inspection, type of mucking system (conveyor or muck cars) to allocate time for muck transportation, TBM state like refurbished or new that effect the overall efficiency of the machine and possible breakdowns, number of motors and their working condition along with the thrust, RPM, power and torque to estimate the penetration rate and boring time, support system to be installed to estimate the time for their installation along the tunnel length.

Project specification should include basic details related to a project like the location, application, total tunnel length, type of excavation method, alignment details, portal specification,

requirement of shafts, in-situ stress condition and basic ground conditions. These serve as elements of different tunneling aspects like surveying, extent of various geotechnical units, excavation specification, construction shift plan, utility extension requirements, approximate quantity estimation of logistics among others.

With the details obtained from geotechnical reports, description regarding the ground type from laboratory and in-situ test, their variability, rock mass properties, quartz content and other ground related details are gathered. These details identifies the probable support system installation along the alignment and their frequency of occurrence, the possible water related issued to be tackled, the type of muck, requirement of cutters among others as shown in Figure 8.3.

The input details discussed above play a vital role in determining the excavation machine utilization and ultimately the project completion time. These details should be obtained beforehand so that an approximate estimation can be made. As the construction proceeds, time allocation for various tunneling activities are obtained and the estimation can be further optimized.

In case the data of project in proximity is available, more accurate estimation of completion time may be made. However, the result depends on the level or elaboration of data acquired. For example, if the approximate ground condition and support requirement is available, the time allocated for performing this activity can be anticipated. Similarly, if the details regarding the crew are available, crew efficiency can be anticipated that is also one of the key elements.

8.6 Case study

Introducing a common methodology for data collection can help in its easy processing for further use. Various sets of data were studied from different projects throughout the world including those from Iran and different parts of United States. The level of detail obtained for these data sets varied significantly and therefore consistency in data interpretation becomes difficult as

a different approach needs to be followed for each case. In the present study, the detailed data from the seven projects listed in Table 8.2 were studied, and an assessment was made on the level of input details to be obtained from the proposed methodology.

Table 8.2. Projects considered in the analysis

Sr. No	Projects	Country	Year of construction
1	Karaj water conveyance tunnel	Iran	2009
2	Nowsood water conveyance tunnel	Iran	2016
3	Stillwater mine project	Montana, US	2019
4	C11 inbound and outbound tunnel	Buffalo, New York	1980
5	C31 inbound and outbound tunnel	Buffalo, New York	1980
6	Chicago TARP	Chicago	1980
7	Culver-Goodman tunnel	Rochester, New York	1981

The details of data available for these projects are given in Table 8.3. The data for Karaj water conveyance tunnel project and Nowsood water conveyance tunnel project was obtained from TBM operator sheets, specification reports, geology maps, daily site reports, geotechnical reports and site engineers' report that was processed further for utilization estimation. The downtimes of tunneling activities with detailed description of the geology was made available. This level of detailed data is termed as Level 4 data as per Abd-Al Jalil (1998) and can be set as direct input in the "processes" modules as shown in Figure 8.3.

The Stillwater mine project data was obtained from daily reports, geotechnical profile and specification report. A site visit was also conducted for 2 weeks and time allocated to each tunneling activity was gathered which was further compared with those obtained from the TBM operator sheets and daily reports to understand the discrepancy. The collected data also included the 4 crews that were working in the tunnel alternatively. This level of data can also be termed as Level 4 data as per Abd-Al Jalil (1998).

Table 8.3. Details of data available

Project	Karaj	Nowsood	Stillwater	C11 and C31 tunnels	Chicago TARP	Culver Goodman
Geology	Lithology	Lithology	Lithology	Lithology	Lithology	Lithology
	Engineering Rock mass Unit	Engineering Rock mass Unit		Engineering Rock mass Unit	Engineering Rock mass Unit	Engineering Rock mass Unit
	RMR	RMR	RMR	RMR (calculated)	RMR (calculated)	RMR (calculated)
	Number of discontinuities		Number of discontinuities	Number of discontinuities	Number of discontinuities	Number of discontinuities
	Average spacing of discontinuity					
	RQD	RQD		RQD	RQD	RQD
	UCS	UCS		UCS	UCS	UCS
	Sigma-global of rock mass					
	Ground water condition					
	Clay					
	Quartz					
		Gas				
TBM type	Double shield	Double shield	Open	Open	Open	Open
TBM specification available	Yes	Yes	Yes	Yes	Yes	Yes
Advance rate	Advance	Advance	Advance	Advance	Advance	Advance
Length	Chainage	Chainage	Chainage	Chainage	Chainage	Chainage
Boring time	Net boring	Net boring	Boring	Boring	Boring	Boring
Segment regrip	Re-stroke/regrip	Re-stroke/regrip	Grippers (timber behind gripper)	Stroke Recycle	Stroke Recycle	Stroke Recycle
Routine maintenance	Washing & cleaning /routine maintenance	Washing & cleaning /routine maintenance	Clean TBM	TBM maintenance	TBM maintenance	TBM maintenance

Table 8.3 Continued

Project	Karaj	Nowsood	Stillwater	C11 and C31 tunnels	Chicago TARP	Culver Goodman
Survey	Surveying delays	Survey problems	Survey	Surveying delays	Surveying delays	Surveying delays
			Guidance delays			
Ground support	Support placement (segment installation)	Support placement (segment installation)	Shotcrete	Ribs/lagging	Ribs/lagging	Ribs/lagging
	Segment delay			Gripper/Rock Reaction	Gripper/Rock Reaction	Gripper/Rock Reaction
	rock jam / clean muck from cutter head/cutter check	rock jam / clean muck from cutter head/cutter check		Scaling/Muck Jam	Scaling/Muck Jam	Scaling/Muck Jam
	clear rock fallout	clear rock fallout		Bolt drills	Bolt drills	Bolt drills
	Cutter change	Cutter change	Cutter inspection & change	Cutter change	Cutter change	Cutter change
	ground improvement /foam injection	ground improvement/foam injection	Grout	Bolts/strap/channel	Bolts/strap/channel	Bolts/strap/channel
	Water inflow problems	Water inflow problems	Water (flowing outside portal too)	Water Inflow	Water Inflow	Water Inflow
	Probe drilling or other drilling	Probe drilling or other drilling	Probe drill	Probe drill	Probe drill	Probe drill
Others	Shift change and safety meeting	Shift change and safety meeting	Travel & meetings	Shaft Operations	Shaft Operations	Shaft Operations
	Lunch & sandwiches	Lunch & sandwiches	Housekeeping			
Crew details available	No	No	Yes	No	No	No

Table 8.3 Continued

Project	Karaj	Nowsood	Stillwater	C11 and C31 tunnels	Chicago TARP	Culver Goodman
TBM back-up	Hydraulic & related problems	Hydraulic & related problems	Pump hydro oil	TBM Hydraulics	TBM Hydraulics	TBM Hydraulics
	mechanical & related problems	mechanical & related problems	TBM mechanical	Cutterhead Motors	Cutterhead Motors	Cutterhead Motors
	electrical & related problems	electrical & related problems	TBM electrical	Electric Systems	Electric Systems	Electric Systems
	Lack of materials	Lack of materials	Supplies			
	conveyor problems	conveyor problems	Equipment (conveyor or muck car)	TBM conveyors	TBM conveyors	TBM conveyors
	utility installation (water, air , power)	utility installation (water, air , power)	Ventilation	Utilities	Utilities	Utilities
			Cable bolts (Stuffed cables)			
			Vent cassette installation			
			Pump oil / drills/ main tank TBM			
Transportation	Transportation & unloading	Transportation & unloading	Wait on train	Train delay	Train delay	Train delay
	train exchange	train exchange	Ties/segment, rail	Trailing Conveyor	Trailing Conveyor	Trailing Conveyor
	derailment	derailment	Train derails	Derail	Derail	Derail
	track placement & problems	track placement & problems	Muck invert	Car Pass	Car Pass	Car Pass
			Muck bound	Clearance	Clearance	Clearance

For C11 and C31 inbound and outbound tunnels, Chicago TARP and Culver Goodman tunnels, the data was obtained from thesis of Nelson (1983). Digitization of graphs showing the downtimes of TBM face and back-up area was done. The geological profile mentioned was not so detailed and an average value of rock mass properties was available. Therefore, the accuracy of the inter-relationship of the downtimes with geology was compromised for these projects, only one document was referenced which had processed data.

For the analysis of these seven projects, it was critical to understand the source of data and how the data are interconnected to each other. The use of variable terminology for similar tunneling activities, and inconsistency in the level of data collection was apparent in all the projects. In order to have an accurate utilization estimation, it is necessary to have a common set of consistently formatted data that can easily be analyzed and referenced for future purposes. The sensitivity analysis as mentioned by Khetwal et al. (2020a), shows the interconnection of various activities and justifies the level of data collection required to estimate the utilization accurately. A list of tunneling activities are prepared as shown in Figure 8.3 that is integrated in the user interface and uniform data template.

8.7 Database template

The data template prepared for gathering input parameters for the simulation model is given in Figure 8.4. The modules are prepared using VBA. The data template should be subdivided into individual geotechnical units because time allocation to many activities are associated with the variation in the ground condition. For example, the boring or excavation time, the support installation time, the type of muck (containing water or soil or are sticky), cutter inspection frequency and cutter change requirements can be associated with the prevailing ground condition. The time allocation regarding utility extension, regular machine check-up, routine maintenance,

surveying, electrical, hydraulic and mechanical check-up and maintenance, transportation of muck and supplies, installation of California switches are more strongly dependent on tunnel length and distance of excavation face from the portal. Therefore, the two factors, geotechnical units and tunnel length are combinedly used to prepare the input template. Other factors like unexpected breakdown of machine and other equipment, crew details are not dependent on any of the two factors and therefore can be set as a random event with certain frequency of occurrence.

A template for the categorization of tunneling activities is listed in Table 8.4 for hard rock TBMs. Recording the time allocated to these activities can improve the estimation of utilization. The data template as proposed in Table 8.4 can serve as the TBM operator shift report for an ongoing project and the data can be directly used in the simulation model as proposed in Khetwal et al. (2020b) and Frough et al. (2019). The list can be extended further pertaining to specific site specifications. The time allocated to these distributions can be analyzed further to obtain the time distributions that can be fed into the simulation model for utilization estimation. The proposed time distributions can be used judiciously considering the site conditions and ground conditions. It is however recommended to gather data of similar project and prepare new set of time distribution to have a more accurate utilization estimation.

Step 1

General information

Project Name	Stillwater
Location	Montana
Application	Others
Ground type	Hard
Excavation diameter	>5m&<=8m
Segment installation required	No
Tunnel length in km	7
Tunnel excavavtion slope	Uphill
Mucking type	Train
Stroke length in meters	1.3
No. of Geotechnical units	10
Radius of curve (m)	0

Autofill Clearall

SAVE CANCEL

Step 2

TBM specification

TBM type	Slurry
TBM condition	Direct_reuse
No. of motors working	6
Cutterhead diameter (m)	6.5
Thrust	3000
RPM	7
Power	300
Torque	2450
Cutter size (mm)	432
Shield length (m)	6.5
TBM backup length (m)	70

Clearall Assign

Save Cancel

Step 3

Geotechnical

Geotechnical Unit Name	mdg
RQD (%)	55
Uniaxial Compressive Strength (MPa)	1400
Indirect Tensile Strength (BTS) (MPa)	140
Elastic Modulus of intact rock (MPa)	28000
Strength of rockmass (MPa)	180
Elastic Modulus of rockmass (MPa)	10000
Quartz content (%)	5
Cerchar Abrasivity Index	3.2
Average RMR	60
GSI	100
Q value	95
Distance from portal / shaft location (m)	35000
Length (m)	4000
Major geotechnical issue	Excessive abrasion
Ground troubleshooting measures	Cutter change/wear

Cutter change/wear
Release TBM
Degas tunnel
Clear rockfall
Clean cutter head
Dewater tunnel
N/A

Autofill Assign Ok

Step 4

Transportation

No. of rails	3
Total no. of trains	4
Total no. of California Switches	4
No. of trains active	3
No. of California Switches active	2

Assign Clearall

Save Cancel

Figure 8.4 Modules in VBA for data collection for individual geotechnical unit

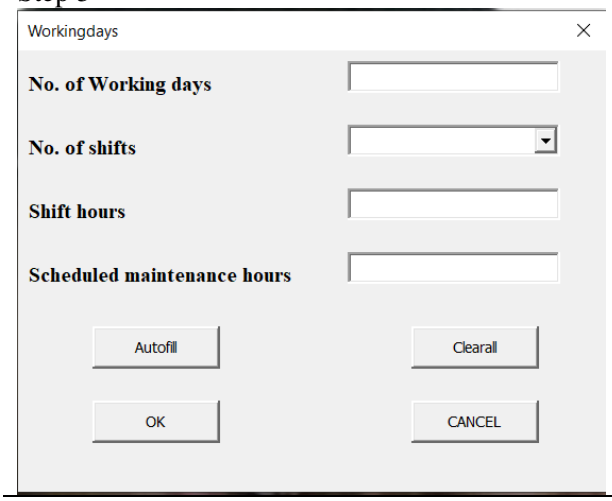
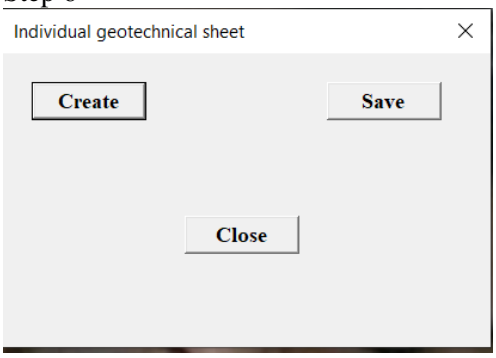
Step 5	Step 6
	

Table 8.4. Data template – list of tunneling activities

Parameters	Activities
TBM specification	Thrust
	Power
	RPM
	Number of motors working
Stroke length	Stroke length
Excavation	Boring
Ground troubleshooting	Rock bolts installation
	Wire mesh installation
	Grouting
	Rockfall clear at invert
	Clean cutterhead
	Cutter inspection and change
	Segment installation
	Water proofing membrane installation
	Regrip
	Probe drilling
	Shotcrete
	Water inflow issues
	Other ground troubleshooting
Utilities	Mechanical
	Electrical
	Hydraulic
	Water pipe
	Ventilation cassette installation
	Power cable stacking

Table 8.4 Continued

Parameters	Activities
Maintenance	Routine maintenance
	Regular Clean TBM
Transportation	Waiting for train
	Derailment
	Train pass
	Track placement and repair
	Muck dumping
	Supplies delay
Survey	Surveying delay
Miscellaneous	Shift change
	Safety meeting / daily progress meeting
	Lunch break
Unexpected breakdown	Other Unexpected delays
	Failure of equipment
Crew	Effect of crew

8.8 Conclusion

The significance of data collection for future references is acknowledged by many researchers and an attempt is made in this study to propose a uniform data collection framework to the tunneling industry. The various tunneling activities contributing to the estimation of machine utilization is identified and their interdependencies are studied. The source of data required for estimation are the various pre-construction reports, geotechnical profiles, TBM operator sheets and shift reports among others. Interpretation of these reports are made so that the input parameters for the utilization estimation can be extracted. For that a VBA based user interface is proposed and geotechnical data sheets pertaining to individual geotechnical unit for a project is obtained. Using this info, the information is fed into the data template and time distribution of individual activity is proposed. The proposed time distributions for the tunneling activities can be used by comparing the site conditions and geology of the area. This time distribution is fed into the simulation model to get the final output which is machine utilization. The proposed framework can develop consistency in the prediction of TBM system performance.

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CHAPTER 9

COMPARISON OF ARENA© SIMULATION MODEL WITH MATLAB CODE

9.1 Abstract

Verification of simulation model can be performed by comparing it with a similar model with same input variables. In the present study, CSM2020 DES model for prediction of TBM utilization prepared using Arena© is compared with the MATLAB simulation code to assess the reliability of the model. The utilization of a hypothetical project was compared using the two simulation models and variation of 0.09% was obtained which is acceptable in the tunneling industry. However, MATLAB code for DES simulation of TBM operation does not have the limits of the Arena© simulation while it allows for running of the simulation without the need for license for Arena©, also offers better opportunity to keep track of the activities in a database that can subsequently be analyzed to evaluate utilization and availability of individual components. The trade-off is losing the analysis of activities and built-in capability of Arena© for simulating a process, including animation and Monte-Carlo modeling. Combining the two system allows for higher flexibility in using DES simulation for assessment of TBM utilization in a given project.

9.2 Introduction and background

The great strength of simulation lies in the ability to explore the "what-if" scenarios. The simulation results capture the randomness of the real system which often makes it hard to interpret and therefore comparing the two simulation models verifies its authenticity and reliability for future use. The widespread application of simulation model include the evaluation of the system, comparison of the existing systems or procedures, prediction of its performance under certain conditions, determining the extent in which factors influences the system, optimizing a system to

produce its best response, and discovering the bottlenecks in the system (Law et al., 1991). The present paper aims at verifying the code generated using MATLAB and the simulation model prepared using Arena© software.

9.3 Assumptions in MATLAB code

The assumptions made in the MATLAB code are made based on the available data from the projects and site visits and interviewing the experts.

- The speed of the train is considered as constant, equal to 15 km/hour.
- The distance from portal to muck dumping yard is considered as 30 m away.
- The TBM backup length is considered as 80 m
- The time taken to dump muck is considered constant as equal to 30 minutes.
- The train with muck cars is capable to carry muck from one cycle and therefore the trains do not need to be changed during one full cycle.
- Only 3 California switches and 3 trains are considered.
- First California switch is installed at a distance of 1 km from the portal, while second one is at 3 km and 3rd one is at 7 km from the tunnel portal. Currently, these positions are fixed. However, it can be made variable based on the site specification.
- The construction of shaft is not considered in the analysis. The tunnel excavation is assumed to start directly from the portal.

9.4 Description of functions

The simulation code in MATLAB is divided in nine modules as discussed here.

9.4.1 Simulation function

All the tunneling activities are combined here and results are obtained using Monte Carlo simulation. The function first reads the tunnel length and the initial distance from the portal. Then it reads the stroke length within which all the tunneling activities are performed. This cycle is repeated for a given geotechnical unit after which the simulation moves to next geotechnical unit. All these data are fed from an MS Excel file that is obtained using VBA code. The Excel spreadsheet will be the user interface to control the input parameters.

9.4.2 Boring function

This function reads the penetration rate and stroke length from the MS excel file prepared using VBA code and calculate the boring time and total distance from the portal which is used in other modules as input.

9.4.3 PreBor function

This function reads the type of muck transportation system used. If conveyor belt is used, then the utilization / availability time of the belt is used in the analysis. If the muck transportation system is train, then an additional function of muck dump is added in the analysis.

9.4.4 Geology function

This function reads the geotechnical unit in which excavation is performed. The function then determines the possible ground troubleshooting measures that can be performed in that unit and allocates time accordingly. This time allocated to each ground troubleshooting measure is calculated as shown in simulation Chapter 4.

9.4.5 Probe drilling function

In this function, the choice of three types of rod length as given in the Arena© is given and their frequency of occurrence is defined accordingly. It is however assumed that continuous probe drilling will be performed along the tunnel length.

9.4.6 Utility extension function

In this function, three types of utilities namely ventilation, power cable and water pipe extensions are considered with their frequency of occurrence at every 200 m , 100 m and 50 m respectively. The time allocated to these activities are as given in Chapter 3.

9.4.7 Transportation system delays

This function takes into account the delays in the transportation system like derailment, track replacement, unloading and reloading and laying rails.

9.4.8 Trains

In this function, the number of trains and the California switches are assigned as the tunnel length increases. This function is considered in the analysis only when the muck transportation system is train. The cycle starts when the train is available at the backup area and is completed when the train returns back to the backup area after dumping muck. In case of 2 trains, one train is considered to be at the portal while second one is at the portal. In case of 3 trains, the third train is placed at the dumping area which is considered 30 m away from the portal location. A constant speed of 15 km/hour is taken for all the trains.

9.5 Methodology

The purpose of this code is to understand how different activities are interacting with each other in the Arena© simulation model. This also serves as a verification of the simulation model prepared using Arena©. The code is designed to encompass the variability in the tunneling activities through distributions and conditions that interconnect these activities and their frequency of occurrences. The data for the code is taken from the projects as discussed in Chapter 8. The time distributions are taken same as those mentioned in Chapter 4.

9.6 Case study

For the purpose of comparing the 2 models, a hypothetical project having three geotechnical units were considered in the analysis as shown in Table 9.1 as obtained using VBA code.

Table 9.1. Details of the hypothetical projects examined by the two simulation programs.

	Unit 1	Unit 2	Unit 3
Project Name	A	A	A
Location	CO	CO	CO
Application	Road	Road	Road
Ground type	Hard	Hard	Hard
Excavation diameter	4.5	4.5	4.5
Excavation diameter range	>3m&<=5m	>3m&<=5m	>3m&<=5m
Segment installation required	Yes	Yes	Yes
Tunnel length (km)	3	3	3
Tunnel slope	Uphill	Uphill	Uphill
Mucking method	Train	Train	Train
Stroke length (m)	1.5	1.5	1.5
No. of geotechnical units	3	3	3
Radius of curve (m)	2000	2000	2000
TBM type	Double_Shield	Double_Shield	Double_Shield
TBM condition	New	New	New

Table 9.1 Continued

No. of motors	6	6	6
Cutterhead diameter (m)	4.5	4.5	4.5
Thrust	17000	17000	17000
RPM	11	11	11
Power	1250	1250	1250
Torque	2500	2500	2500
Cutter size (mm)	432	432	432
Shield length (m)	6.5	6.5	6.5
Backup length (m)	80	80	80
No. of working days	5	5	5
No. of shifts	2	2	2
Hours per shift	10	10	10
Scheduled maintenance (in hr)	4	4	4
Geotechnical units name	G1	G2	G3
RQD	70	70	35
UCS	50	70	100
BTS	10	10	10
Elastic Modulus of Intact rock	15000	16000	17000
Rock mass Strength	50	60	70
Elastic modulus of Rock mass	10000	10000	10000
Quartz content (%)	5	5	5
Cerchar Abrasivity Index	3	3.5	4
Average RMR	80	70	60
GSI	35	40	45
Q value	1	1.5	2
Distance from portal (m)	0	1000	2000
Length (m)	1000	1000	1000
Penetration rate (m/hr)	3.5	2.5	3
Major geotechnical issue	Collapse & instability	Groundwater flow	Excessive abrasion
Ground troubleshooting measures	Rock bolt wire mesh	Dewater tunnel	Cutter change/wear
Type of muck conveyance system	Train	Train	Train
No. of rails	1	1	1
Total no. of trains	2	2	2
Total no. of California Switches	1	1	1
No. of trains active	1	1	2
No. of California Switches active	0	0	1

9.7 Comparison of results from Arena© and MATLAB

The utilization and completion days estimated by the two simulation programs are compared in Figure 9.1. It can be seen that the p-value of the two results are 0.817 which is much higher than the significance level of 0.05. Table 9.2 shows the comparison results with the range of values in 95% confidence interval. Variation in the fourth decimal can be seen and hence the two simulation models complement each other.

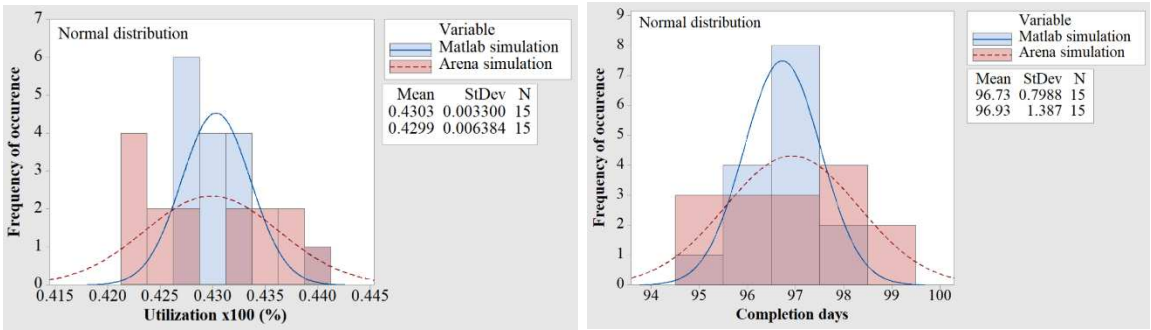

Figure 9.1. Comparison of Arena© and MATLAB simulation results

Table 9.2. Comparison results

Factor	Number of replications (N)	Mean	Standard Deviation	95% CI
MATLAB simulation	15	0.4303	0.0033	(0.4277, 0.4330)
Arena© simulation	15	0.4299	0.0064	(0.4272, 0.4326)

After interpreting the results, following other factors can be pointed out for comparison of the two simulation methods.

- The MATLAB code can read values from the MS excel easily which was very difficult for Arena©.

- For running 15 replications, it took 30 hours for Arena© while for MATLAB it took almost 40 hours on a typical desktop computer, showing that the Arena© can be faster in offering the simulation results. However, with powerful computers, this time can be reduced significantly.
- The Arena© software is compatible with only Windows PC while MATLAB can run in any operating system.
- The Arena© software available can be used for non-commercial purposes only while no such restriction is for use of MATLAB.
- The graphical interface of Arena© is stronger than MATLAB. However, with the use of Simulink, which is part of MATLAB, visual animation can be made. This was however, not done in the present study.
- The cost of Arena© software is almost 5 times that of MATLAB.
- The use of Arena© simulation model require training as for changing 1 input various other locations need to be cross checked in order to avoid any possible error. For example, if the number of trains are changed, their start location, sequence of their travel needs to be changed and verified. This is very simple in MATLAB if proper notations are given.
- The most important factor that Arena© does not have is the capability to increase the number of trains with increasing length as trains are fed as transporter in the model and not as a separate module. This means that if the number of trains are increasing with increasing length, the lengths need to be divided accordingly and so is the number of simulation models. However, since California switches are modelled as module, its activation can be controlled on the basis of the tunnel

length. This limitation is not an issue in the MATLAB code as the number of trains can be increased with the increase in tunnel length and can be modified as per the project requirement.

9.8 Conclusion

The important step in preparation of a simulation model is its verification. The present study aims at comparing the two simulation models that's are prepared using Arena©, a discrete event simulation software and a MATLAB code developed to perform DES simulation. Comparing the results of a hypothetical project showed a variation of 0.09% in utilization estimation with a p-value of 0.817 making the results to be within acceptable limits. The variation can be attributed to the fact that while in Arena©, the crew efficiency was considered as an extra time allocated in each shift, it was incorporated in terms of a flat percentage efficiency of 0.9 in MATLAB. With the increasing number of replications and further comparison of the result of both modeling approaches for real projects, one can further validate these two models and assess their capabilities.

9.9 References

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CHAPTER 10

CONCLUSION AND RECOMMENDATIONS

10.1 Conclusion

Predicting the performance of tunnel boring machine (TBM) is paramount to proper selection of the machine specifications, operation of the machines, and estimation of time of completion, hence the cost of tunneling. The performance of a TBM can be assessed by estimating its utilization for given period like a shift or a day, a reach of tunnel with given slope of curvature, a certain geology and ground condition, or the entire project. While there are various models that are able to predict TBM utilization, none of the existing models encompass all the critical activities that affect the estimation. The existing models are empirically based models that do not account for the uncertainties like the variation in the support installation time, utility extension requirements, transportation system etc.

Discrete event simulation has proven to be a promising approach as can be seen in the DAT simulation software (Einstein, 2002) and by Abd-Al Jalil (1998) in predicting TBM utilization. DES approach has the capability to consider events as individual activities and determine their interdependencies. The uncertainties in the input parameters are taken into account by assigning the activity time through stochastic modeling, and to see the impact of various site setting on TBM utilization.

The main objective of the present study was to facilitate estimation of machine utilization using DES approach. A platform for utilization estimation was developed based on the available data from nine projects where hard rock TBMs (double shield and open machines) were used. A data collection framework is prepared using MS excel built-in VBA program, where data from project reports can be pre-processed to estimate the activity time for DES modeling for future

projects. Variables such as ground conditions, TBM specifications, and site logistics can be defined along with the other factors like the type of transportation system, requirement of probe drilling, number of working days, shift duration for each geotechnical unit. This individual geotechnical data sheet is set as input in the simulation model.

The simulation models were prepared using Arena© software and MATLAB code for verification. The Arena© simulation software is a DES based industrial software that has widely been used in a variety of applications including the mining industry for simulation of the operation in open pits mines and therefore its further application in tunneling is assessed in the present study. The simulation is based on an entity, which, in this study was selected to be the stroke or extent to which tunnel is advanced by excavating one cycle. Hence, the stroke represents the smallest unit of operation. The train or conveyor belt could be used as the muck conveyance system. The tunneling activities considered in the simulation model are ground troubleshooting measures, TBM and backup maintenance, transportation of supplies and muck with train and California switches were modeled to allows for train by passing when single tracks were used in tunneling, utility extensions, surveying, probe drilling and other unforeseen breakdowns. Individual modules were made for these activities and the time allocated to them were obtained from the nine projects where TBM was used for excavation of the tunnel. Crew experience was also considered in the model in terms of the possible overall delays that can happen in a shift. Time distributions of these activities were evaluated and assigned based on the machine type and site setting to encompass the uncertainty in the input values.

A sensitivity analysis was performed to assess the interrelationship between the different tunneling activities. The analysis showed that utilization varied when same geotechnical unit was located at different distance from the portal. It proved that if the ground conditions involve poor

rock masses, as represented by RMR below 30 at the portal, the utilization is not affected as much, while it reduces when such poor ground conditions occur after certain distance from the portal. The utilization showed maximum sensitivity towards maintenance as it contributed to around 19% of the total downtime.

The CSM2020 simulation model that is a DES model of TBM operation using Arena software was verified by a compatible DES simulation model developed by MATLAB code. Comparing the result of both simulation models in terms of TBM utilization for various reaches of tunnel in certain geological settings showed variation of 0.09% between the two systems, hence is considered acceptable for its use in estimation of TBM utilization for tunneling projects.

Overall, the results of the studies can be summarized in the following conclusions.

- Use of DES modeling can offer a quantitative system for incorporating variety of scenarios involving geology, machine specifications, backup system, and site logistics and setup in estimation of machine utilization
- The DES modeling offers the flexibility to incorporate unknown geological conditions, new machines and sub-systems, crew experience, the impact of using new or used machines and TBM launching system (portal vs shaft) in the calculations and evaluate the pertinent risks and utilization of subsystems in the tunneling operation during the operation.
- The simulation allows for identification of bottlenecks and to evaluate the cost of implementing changes in the system versus potential gains/losses in operation, as represented by machine utilization.
- In general, the DES model can be further developed to be used as part of a system for optimization of tunneling operation and selection of TBMs with a quantitative

approach to evaluate various features of the machine and backup system for improved operation and increased daily advance rates.

10.2 Future work

The scope of the simulation models presented in this study can be extended in following ways:

- Extension of the simulation model by adding new tunneling activities as modules such as other types of utility extensions, increasing number of rails, transportation system using rubber tired vehicles.
- Simulating different types of backup systems, TBM types, ground conditions (hard, soft and mixed) an comparing their utilization values that will help in the TBM selection and decision making process that is related to individual TBM or backup components or their capabilities/capacity
- Incorporating the different ground conditions, as represented by soft ground or rock mass types with variable properties. This will provide the flexibility to simulate the utilization under variable ground conditions. For example, the fault zone or similar extreme ground condition can be added to the simulation model that can also be accounted for in the risk registry for the extra time allocation related to handling the adverse conditions.
- Integration of simulation results in the DAT software. At present, the DAT software has utilization value as one of the input that is based on the understanding and experience of the engineer using the software and therefore the estimated value obtained from the present simulation model could be more realistic, based on the TBM, site setup, and geological issues.

- Identifying the bottlenecks in the project that requires attention to assess the limits on the operation and to suggest changes that can lead to an efficient tunneling operation. This requires an additional module that can summarize the utilization of the components and analyze the activity times and highlight the potential capacity issues. This will help the contractor in resource allocation process and to have a good contingency plan.
- Implementation of the simulation results in risk registry to encompass the uncertainty in terms of project completion and other possible bottlenecks.
- Expand the database of machine field performance to include applicable time distributions of the tunneling activities for variety of machines and backup system configurations and geological settings. At present, time allocation of some activities such as dumping muck, crew efficiency, portal and shaft activities, supply chain issues are based on general experience and need to be modified based on field observations and time studies.
- Develop a support module to allow the DES simulation to be used for optimization of the operation or quantitative assessment of the machine/backup components and to allow for objective assessment of the various machine types and special features.
- Comparison of time distributions for selected critical activities to assess the sensitivity of the models towards change in the distribution functions.

APPENDIX A

PERMISSION FROM AUTHOR

Anuradha Khetwal <akhetwal@mymail.mines.edu>

Permission to publish papers as part of thesis

3 messages

Anuradha Khetwal <akhetwal@mymail.mines.edu> Wed, Jan 20, 2021 at 10:36 PM
To: Omid Frough <omid.frough@gmail.com>

Dear Omid,
Since I am adding published papers of which you are author too in my thesis, I will needing permission ftom you allowing me submit the papers as part of my thesis.
Thank you for confirming this.
Regards
Anuradha

Omid Frough <omid.frough@gmail.com> Wed, Jan 20, 2021 at 10:45 PM
To: Anuradha Khetwal <akhetwal@mymail.mines.edu>

Dear Anu,

I grant permission to publish the papers as part of your thesis.

All the best
Omid Frough
[Quoted text hidden]

Anuradha Khetwal <akhetwal@mymail.mines.edu> Wed, Jan 20, 2021 at 10:50 PM
To: Omid Frough <omid.frough@gmail.com>

Thanks a lot Omid
Regards
Anuradha
[Quoted text hidden]