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Probabilistic Risk Assessment and Prediction of Delay in Conventional Tunnelling

A Thesis in MSc. Railway Engineering (Civil Infrastructure)

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A Thesis

Submitted in Partial Fulfilment of the Requirements for the Degree of Master of Science

CERTIFICATION

The undersigned have examined the thesis entitled '**Probabilistic Risk Assessment and Prediction of Delay in Conventional Tunnelling**' presented by **JOY KIRINDA**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that research work titled "**Probabilistic Risk Assessment and Prediction of Delay in Conventional Tunnelling**" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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ABSTRACT

In this study, first of all, definitions of main term such as “risk”, “risk analysis”, “risk event”, “consequence” and “likelihoods” were made to avoid any confusions about these terms, and significance of risk analysis and management in engineering projects was emphasized. Then, both qualitative and quantitative risk analysis techniques were mentioned and within scope of the study, Severity Risk Analysis, Monte Carlo Simulation and Discrete Event Simulation methods were selected in order to analyze the risks regarding Conventional Drill and Blast tunnelling and their impacts on construction schedule. After all hazards that would be encountered during tunnel construction by Conventional Drill and Blast tunnelling had been identified, a preliminary risk analysis to sort out and prioritize ‘intolerable’ risks was conducted. When risk scores were taken into consideration, it was seen that ‘intolerable’ risks to schedule could be classified into five groups that are; accidents, labour disputes, defective work, delay of material delivery and plant and machinery failure. According to these five classified groups of risks, a correlation analysis using Decision Making Trial and Evaluation Laboratory and Schedule Delay Analyses using Monte Carlo and Discrete Event Simulation techniques was conducted. Finally, the results of the Schedule Delays predicted by the quantitative risk analysis techniques of Severity, Monte Carlo Simulation and Discrete Event Simulation were validated and interpreted together by making comparisons against actual durations from Awash-Kombolcha-Hera Gebeya Railway project by considering the Root Mean Square Error. The results showed that the Discrete Event Simulation model developed was a superior method of predicting tunnelling delay followed Monte Carlo Simulation and lastly Severity Analysis respectively.

Keywords: Conventional Drill and Blast Tunnelling, Risk Identification, Severity Analysis, DEMATEL, Monte Carlo Simulation, Discrete Event Simulation, Root Mean Square Error.

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LIST OF ACRONYMS

ABM	Agent-Based Model
AK-	Awash-Kombolcha
DAT-	Decision Aids for Tunnelling
DEMATEL-	Decision Making Trial and Evaluation Laboratory
DES-	Discrete Event Simulation
MC-	Monte Carlo
MCS-	Monte Carlo Simulation
MIT-	Massachusetts Institute of Technology
RMSE-	Root Mean Square Error

CHAPTER 1: INTRODUCTION

1.1 Background

The construction of tunnels is associated with some of the highest risks of any type of construction due to the uncertainty of the subsurface geological and groundwater conditions and the inability to confirm all the conditions along a proposed tunnel prior to the construction of the tunnel (Brox, 2017). Tunnels are indispensable during the installation of railway infrastructure in hilly terrains such as those along the Awash-Kombolcha-Hara-Gebeya route (intended to link Northern and Central Ethiopia) and in congested areas such as Piassa in Addis Ababa where Menelik II tunnel is located. Over the past six years, there has been a significant increase in the building of railway tunnels in Ethiopia. For instance, the capital of Ethiopia, Addis Ababa did not even own a railway network before 2015. However, six years later, Ethiopia has a systematic Light Rail Transit network with a tunnel at Menelik II and twelve other tunnels under construction along the Awash-Kombolcha-Hara-Gebeya Railway Line.

It is relatively difficult to construct tunnels in all types of locations and most importantly, it is common for any forms of risk to occur during tunnelling. Historically, tunnel construction has resulted in some serious accidents with damage to construction equipment, adjacent and overlying infrastructure, and injuries to workers (Brox, 2017). Tunnelling imposes risks on all parties involved directly or indirectly in the project. These risks may dramatically influence operations of tunnel construction especially in major cost and time delays (Lee Yong Siang, 2017). A study conducted by (Wakjira, 2011) concentrated on the risk factors leading to cost overrun without conducting any time impact assessment due to risk occurrence. However, the recognition that some resources such as labor, rented equipment and project administration's response to risks to schedule (AACE, 2011) should be a driving force towards risk management for any tunnelling project. This is owing to the fact that they cost more if they are engaged on a project longer than planned rendering schedule delay as an undesirable occurrence.

Risk management for tunnel projects has become an increasing established practice using various available tools and should be recognized and accepted by all parties to a contract. Risk management is a beneficial process that promotes the implementation of a culture, processes and structures directed towards realizing potential opportunities, identify the

hazards and minimize their adverse consequences through effective planning and mitigation measures. First principles require that project schedule delay be clearly and directly driven by identified and quantified risks. The occurrence of these risks may affect time, cost and method of performance of the parties involved in the project and will ultimately affect the project schedule, either increase the overall project duration or decrease it. Decreasing the project duration would be every Project Manager's dream. On the contrary, increasing the project duration far beyond the schedule arising out of poor risk assessment is every Project Manager's nightmare. There is need therefore for quantitative prediction of the impact of the risks prior to the commencement of a project in order to give an acceptable level of confidence that the schedule and project costs will not escalate beyond the bounds of the original estimates.

1.2 Statement of the problem

Tunnelling has become a preferred method of construction for railway projects in countries dominated by mountainous geological conditions and dense population such as Ethiopia. However, tunnel construction works are usually complicated and costly, which consequently imposes great uncertainties and risks to the parties involved. Project risk has it its roots in the uncertainty that is inherent in all projects (PMBOK, 2008). These risks in tunnelling have always been the object of attention because of time and cost overruns associated most tunnel construction projects (Farid Ghazali and H.C. Wong, 2013).

There are different types of uncertainties affect tunnelling processes. Estimates of these uncertainties and risks of the tunnel construction process are essential information for decision making in tunnel projects. In tunnel construction, a substantial part of the uncertainty results from unknown geotechnical conditions, applied construction method, and to a small extent human errors and organizational factors. All these uncertainties should be taken into account when modelling the uncertainty and risk of tunnel construction.

Generally, the methods and techniques mostly used on Ethiopian projects to identify, assess, allocate and mitigate the risks are highly dependent on expert opinion. However, these can be strongly biased and unreliable if used in isolation. Therefore, expert estimates should be supported by numerical analysis of risk data from previous projects. As a prerequisite for reliable prediction of uncertainties and risks, it is essential to use input parameters into a risk analysis model for predicting the consequences of risk occurrence

be realistically estimated. The consequences that arise from occurrence of risks and uncertainties in tunnelling may include human injury, damage to property, environment, economic loss and delay in project completion. The occurrence of the risks may be in isolation or as a combination of two or more risks. However, this study shall be limited to estimation of delay in project completion due to occurrence of certain major risks.

The key to controlling risk lies in having a clear comprehension of what is risk, risks relevant to a project and risk acceptance thresholds determined by owners and stakeholders of project. As these three requirements are easy to instruct, they are more difficult to apply in real life. Since these are projections into the future, the best one can do is estimate the expected value. One cannot know with certainty what the actual value will be, but based on historical data, or expertise in the field, or experience; and using probabilistic analysis, an estimate of the amount of time it will take to complete a tunnelling project can be drawn with a certain level of confidence. Additionally, many of the scheduling packages now in use assume deterministic systems. Use of simulation as an originator to scheduling permits consideration of probabilistic events as well. Despite the efforts to invent a number of simulation tools, construction simulation remains at academic level due to the complexity of simulation methodologies and complexity of the construction process itself (AbouRizk S. M., 2008).

This research helps fill the gap by introducing a flexible model for simulating risk occurrences that can be used to predict the impact on the schedule. First, it identifies tunnelling risks through case studies where conventional drill and blast tunnelling method has been used. Secondly, it conducts a qualitative analysis of risks. Thirdly, conducts deterministic risk analysis based on severity level to select risks that pose the highest consequences. Lastly, it introduces simple probabilistic models for the estimation of delay due to occurrence of construction uncertainties.

1.3 Objectives of the study

General Objective

To develop a probabilistic model for time impact analysis that can be used to forecast the amount of delay arising from occurrence of intolerable risks in conventional drill and blast tunnelling using simulation as a capable tool.

Specific Objectives

- To identify risks in conventional drill and blast tunnelling
- To determine correlations between risks to schedule in conventional drill and blast tunnelling
- To estimate the delay arising from occurrence of the risks
- To conduct a comparative analysis of risk modelling techniques

1.4 Research questions

This research is geared towards responding to the following questions:

1. What are the major risks undertaken by using conventional drill and blast tunnelling method?
2. To what extent does risk occurrence affect the timely completion of a tunnel construction project?
3. What risk modelling technique gives the best results?

1.5 Significance of the study

Academic contribution

Academically, Discrete Event Simulation has had limited application in the study of risk and prediction of delay on construction projects. This research introduces a simple probabilistic model for the estimation of the delay due to occurrence of construction uncertainties based on Discrete Event Simulation.

Industrial Contribution

- The probabilistic risk assessment model will provide an alternative quantitative approach to the Supervision Team for assessing the accuracy of the CPM Schedule for tunnelling prepared by the Contractor.
- Since every construction delay culminates into costs due to the time based project inputs such as equipment hire, labor costs among others, the probabilistic risk assessment model will ultimately allow for the inclusion of the quantified consequences in terms of risk contingency into the construction costs estimate. This will allow for a more accurate total project cost estimate although the cost analysis is outside the scope of this research.
- The parties to a contract can extend the approach proposed to assist in effectively presenting and analyzing claims.

1.6 Research methodology

The research strategy adapted for this research is mixed research of exploratory type which applies both qualitative and quantitative assessments as it diagnoses a situation, assess alternatives, and discover new ideas. The methodology followed for the research has five main parts as described hereunder.

i. Literature review:

Literature was reviewed for the purposes of obtaining a theoretical basis for the research, formulating the research questions and defining the scope. The main sources of literature were journals, reports, conference proceedings and textbooks relating to drill and blast tunnelling, tunnelling risks, risk modelling and analysis, simulation modelling and delay analysis.

ii. Desk Study

This consisted of gathering information about the risks/hazards faced in the construction of tunnels by conventional drill and blast method. The risks are subsequently grouped according to the consequences on the project so as to identify those responsible for change in schedule through preparation of a risk register. This is mainly done by means of a desk study of past research related to tunnelling risks.

iii. Data Collection

Data collection involved gathering of information about the consequences, likelihoods/frequency of occurrence of hazards, correlations for intolerable risks and 3 point estimates of tunnelling durations. This was mainly done through interviews with experts of tunnelling construction projects using a pre-prepared questionnaire. The information from the interviews would form the basis for qualitative and quantitative risk analysis. In addition, data relating to the As-Planned and As-Built tunnelling schedules were also collected from the site, which would be part of the inputs for the analysis and results.

iv. Analysis and results

This step consisted of conducting the following analyses in line with the research objectives so as to predict delay using various methods:

a) Qualitative Risk analysis
b) Quantitative Risk Analysis through;
    - Risk Correlations and Interrelations
    - Severity Risk Analysis
    - Monte Carlo Simulation using @Risk MS Excel add-in.
    - Discrete Event Simulation using ARENA software
c) Finally, conducting a comparative analysis of the results from the applied risk analysis and delay prediction methods

v. Conclusion and recommendations

This section was aimed at drawing conclusions based on the research findings, and giving any recommendations for application, improvement and/or future work.

The summary of the research methodology is as indicated in Figure 1.6-1 below.

PROCEDURE	OUTPUT
1. Literature Review - Review literature to define the theoretical framework of the research	• Theoretical framework of the research
2. Desk Study - Review past research on drill and blast tunnelling risks	• Drill and Blast tunnelling Risk Register
3. Data Collection - Prepare interview questionnaire - Conduct interviews - Review relevant site documents - Organize data collected	• Risk Consequences • Risk Likelihoods • Risk Correlations • 3-Point Estimates of tunnelling activity durations • Drill and Blast tunnelling Process Map
4. Analysis and Results - Qualitative Risk Analysis - Quantitative Risk Analysis - Comparative Analysis	• Qualitative categorization of risks • Estimation of delay using Severity analysis, Monte Carlo Simulation and Discrete Event Simulation and conclusion on superiority of the methods. • Comparative analysis for use in application of the methods.
5. Conclusion and Recommendations	• Summary of the observations of analysis and results • Recommendations for future work (if any)

Figure 1.6-1 Summary of research methodology

1.7 Scope and limitation of the study

This research is limited to the estimation of delay arising from the occurrence of the most severe hazards while using conventional drill and blast with bench cut tunnelling method by taking Awash-Kombolcha-Hara-Gebeya railway project as a Case Study.

1.8 Thesis organization

This thesis is presented in five chapters. The arrangement of thesis is described below.

- Chapter 1 gives a brief introduction to the research and arrangement of the thesis. The objectives, research significance, the scope and the research methodology are found in this chapter.
- Chapter 2 presents a review of the relevant literature necessary to the research topic and conducting a risk identification process from past research.
- Chapter 3 discusses the design and methodology for the research
- Chapter 4 presents the various risk assessment methods including quantitative risk assessment, severity analysis, Monte Carlo Simulation as well as Discrete Event Simulation using ARENA model. Results and their analysis are also included for each of the different methods and ultimately a comparative analysis of the outcomes from each method.
- Chapter 5 Conclusion and recommendations. In the final chapter the topic has been concluded and further research area has been suggested.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Before a tunnelling construction project can be analyzed, it is important to define the tunnelling system. Decisions have to be made concerning the mode of excavation (e.g. drill and blast, TBM, road-header), the material handling process, and the tunnel support system. In this Chapter, the various activities related to the tunnelling construction process will be explored. The purpose of this literature study is to get a general overview of the different construction processes involved in tunnelling, and the interaction of the various processes in the context of tunnelling construction and to identify risks associated with tunnelling.

In the first section will focus on the definition of common terms to be encountered throughout this report. The subsequent section will be focused on the main excavation methods, namely drill and blast, tunnel boring machine (TBM), and road-header and current tunnelling practice in Ethiopia. The last section of the literature will be focused identification of risks associated with tunnelling and their analysis techniques.

2.2 Definitions

2.2.1 Risk

Some literatures have gone ahead to define risk as a situation or condition that has the potential for unwanted consequences without considering the fact that some consequences may be positive to the project (Eskesen, 2006). A risk is a basic and natural element of life defined, as "the chance of something happening that will have an impact on objectives". Meaning a risk can be either positive in which case it will benefit all or some of the parties to contract or negative in which case it will have detrimental consequences (Rausand, 2011). In quantitative terms therefore, a risk is a combination of the probability of an event occurring and its impact to project objectives.

2.2.2 Risk Analysis

Risk Analysis is a structured process that identifies both the probability and extent of adverse consequences arising from a given activity (Eskesen, 2006). However, (Summers, 2000)

expounded on that definition by including the identification of hazards as the first step and subsequently the description of risks i.e. probabilities and consequences.

2.2.3 Risk Event

Risk Event is a discrete, specific occurrence that negatively affects a decision, plan or project. For example, a delay in supply of materials is a risk event for a construction project.

2.2.4 Contingency

Specific provision for unforeseeable elements of cost within the defined project scope. Contingency is particularly important where previous experience relating estimates and actual costs has shown unforeseeable events that will increase costs are likely to occur (AbouRizk, 2008).

2.2.5 Impact/Consequence

The value of the effect of the risk event, if it occurs, on one or more of the parameters of interest to the involved parties. By assessing the consequences of the outcomes of an event in terms of how they affect the project objectives, the impacts are derived (AbouRizk, 2008).

2.2.6 Opportunity

The possibility of realizing a favorable outcome and the impact of this outcome on the involved party. Opportunity is a positive risk, and it can be identified and managed in similar ways (AbouRizk, 2008).

2.2.7 Severity

Measures the expected value of the impact of a risk event. It is a simple measure for gaining an understanding of the magnitude of risk, as not all risk events are likely to be encountered.

2.2.8 Uncertainty

The gap between the information required to estimate an outcome and the information already possessed by the decision maker (AbouRizk, 2008). Uncertainty refers to ‘lack of knowledge’ about specific factors, parameters, or models (Forum, 1997).

2.2.9 Likelihood

The degree of certainty that a risk event will occur during a specified period of time (AbouRizk, 2008). The likelihood levels can be described as frequency values or with respect to how easy it is for a person to exploit a threat (PMBOK, 2008).

2.2.10 Simulation

It is the imitation of the operation of a real world system or process. Involves the mimicking of a real work system using a computer model.

2.3 Tunnelling

This section gives a general description of the tunnelling techniques that can be used on a project. At present cut and cover, drill and blast, bored tunnelling and sequential tunnelling construction can be considered the most common excavation methods used in tunnelling.

2.3.1 Tunnelling techniques

Cut and Cover Tunnelling

Cut and cover tunnelling is a common and well-proven technique for constructing shallow tunnels. The method can accommodate changes in tunnel width and non-uniform shapes (Brox, 2017). Several overlapping works are required to be carried out in using this tunnelling method. Trench excavation, tunnel construction and soil covering of excavated tunnels are three major integral parts of the tunnelling method. Most of these works are similar to other road construction except that the excavation levels involved are deeper. (David Chapman, 2010) Majority of excavation is often undertaken under a road deck to minimize traffic interruption as well as environmental impacts in terms of dust, noise emissions and visual impact.

Drill and blast method

Drill and blast process is a cyclic operation; each cycle consists of seven major successive operations, namely: drilling, charging, blasting, ventilating, mucking, scaling and installation of primary support. The drilling operation consists of drilling a series of small blast holes in the tunnel face, by a so called “drill jumbo”. The number of holes and location are dependent

of the type and condition of the rock, the type of explosive and the blasting technique used (Likhitruangsilp, 2003). After all the required holes are drilled, they will be loaded with explosives in a process known as charging. Once the explosives are loaded in the blast holes, the tunnel face is cleared and the explosives are then detonated in a process known as blasting. This operation will lead to dust and excavated soil, which must be removed subsequently through ventilation and mucking processes. Mucking machines and materials handling equipment are mobilized, and the muck is hauled out of the tunnel face. Also pieces of loosened rock remaining on the tunnel roof and walls have to be removed by scaling to allow mucking to continue to completion. After the mucking operation, primary support systems are installed to stabilize the opening. Primary support systems are installed at the same time as the excavation operation to keep the opening stable during construction. For the drill and blast method, primary support is usually installed after the mucking operation is completed in each round, but before or during the drilling operation for the next round (Likhitruangsilp, 2003). Final lining is installed at some later stage after the installation of primary support. In general final lining occurs after the tunnel has been entirely excavated and supported. Common lining systems are: monolithic concrete lining, steel segments, and pre-cast concrete segments.

Bored Tunnelling

Bored tunnelling by using a Tunnel Boring Machine (TBM) is often used for excavating long tunnels. An effective TMB method requires the selection of appropriate equipment for different rock mass and geological conditions. The TBM may be suitable for excavating tunnels which contain competent rocks that can provide adequate geological stability for boring a long section tunnel without structural support. However, extremely hard rock can cause significant wear of the TBM rock cutter and may slow down the progress of the tunnelling works to the point where TBM becomes inefficient and uneconomical and may take longer time than the drill-and-blast tunnelling method (Brox, 2017).

TBM tunnelling construction involves three main processes, namely excavation, dirt removal and tunnel support (Ruwanpura J. Y., 2001). The construction of a tunnel (using TBM) begins with the excavation and liner support of the vertical shaft. In the construction of a tunnel using TBM the following operations can be distinguished:

1. Excavation and support of the undercut area

2. Excavation of the tunnel and tail tunnel
3. Disposal of dirt from the tunnel face
4. Hoisting dirt to ground level
5. Lining the tunnel
6. Extending the services and rail tracks
7. Excavation and support of the removal shaft.

Two types of tunnelling boring machines are used in the tunnelling construction practice, namely the open-face and closed-face shielded machines. Both methods are used in different circumstances. The open- face boring machines is used when excavating through stable soils. When the soil conditions become less stable, because the soil consists of for example silt or sand, closed-face shielded machines are used. Important properties in the excavation processes using TBM are the excavation rate and stroke length of the tunnelling boring machine. The excavation rate is dependent on the soil conditions and TBM horsepower. The stroke length determines how often the TBM will need to be reset. Dirt handling involves the transportation and disposal of spoil from the tunnel face to the shaft, from where it is transported to the surface. Different methods are used to haul the spoil from the tunnel face to the shaft; examples are trains and belt conveyors. Using trains to haul spoil has many advantages. First of all it is compatible with most excavating and loading methods, and can be used in almost all sizes of tunnels. Another advantage is that besides hauling of spoil, also labourers and support liners can be transported using trains. Depending on the tunnel diameter, a single or double-track system can be used. Belt conveyors on the other hand have the advantage that it can provide a continuous spoil removal system. The spoil that is hauled to the shaft of the tunnel using trains and /or belt conveyors subsequently has to be lifted up to the surface. Hoisting dirt can be done using different methods, these are: with a skip, a clamshell bucket, a crane, a gantry or a derrick hoist. The working shaft is also used to transport construction material and personnel (Ruwanpura J. Y., 2001).

Two important tunnel support systems consist of rib-and- lagging and concrete segments. The rib-and-lagging support system is used as a primary lining system. When tunnelling excavation is finished cast-in-place concrete is placed as final lining. Pre-cast concrete segment lining acts as primary and final lining. The segments are installed inside the shield of the TBM, and expanded against the soil as it leaves the shield (Ruwanpura J. Y., 2001). For tunnelling by

TBM there are also other primary support systems used, namely: steel sets, rock reinforcement systems, and shotcrete (Likhitruangsilp, 2003).

Sequential Excavation Method

This method is also known as the New Austrian Tunnelling Method (NATM). The excavation location of a proposed tunnel is divided into segments first. The segments are then mined sequentially with supports. Some mining equipment such as road headers and backhoes are commonly used for the tunnel excavation. The ground for excavation must be fully dry for applying the NATM and ground dewatering is also an essential process before the excavation. Another process relates to the ground modifications such as grouting, and ground freezing is also common with this method in order to stabilize the soil for tunnelling. This method is relatively slow but is found useful in areas where existing structures such as sewer or subway could not be relocated (Brox, 2017).

The use of Road-headers can achieve a better advance rate than the drill and blast-method, but significant lower than the tunnel boring machine. The advantages of this method are similar to the TBM method, such as continuous operation, limited non-productive time, and quality of the tunnel opening. However, road-headers are more flexible than the tunnel boring machine, because they can be applied to various types, shapes, and sizes of underground excavation (Likhitruangsilp, 2003).

Tunnelling construction using road-headers involves three main processes, namely: excavation, dirt removal and tunnel support (Obeidat, Al-Barqawi, Zayed, & Amer, 2006) Excavation is done using road-header for a certain amount of time. In order to start the next process the road-header is pulled back. The removal of dirt from the face of the tunnel can be done by using a conveyor belt, trucks or trains. After the road-header has excavated for a certain amount of time it gets pulled back, so that scaling and the installation of mechanical bolts can start. Subsequently installation of initial support is done. This operation involves installation of wire mesh or shotcrete at their designed locations.

2.3.2 Ethiopian Tunnelling Practice

Only a limited number of studies have been conducted in Ethiopia in relation to tunnels. The only study in the records was conducted by (Tesfamichael, 2015) which aimed at developing a

software application that analyzes continuum analytical tunnel lining design and secondary stress around circular opening. This study did not at all consider the tunnelling phase as well as any associated risks.

Tunnelling employs a number of different techniques among which the drill and blast method of excavation typically adopted for the construction of tunnels in rock of length less than 4 km for economic reasons (Brox, 2017). The Awash -Kombolcha -Hara Gebeya Railway Project summary and status report for December 2017 (Corporation, 2017) indicates that the longest tunnel on the project after completion will be Tunnel 14 with length 2,033m (the longest tunnel in Ethiopia) which is well within the 4km for use of conventional tunnelling. This justifies why all the tunnels so far constructed in Ethiopia have applied the Drill and Blast tunnelling technique. None of the tunnels constructed in Ethiopia to date has employed the TBM and Sequential Excavation Methods. This therefore limits the study to drill and blast tunneling technique as applied on Awash -Kombolcha -Hara Gebeya Railway Project.

2.4 Tunnelling Risks and Uncertainties

2.4.1 General overview

According to (Rausand, 2011) risk is defined as “the chance of something happening that will have an impact on objectives”. Meaning risk can be either positive (opportunity) or negative (loss). In this situation, an opportunity would mean early completion while a loss would imply a delay in project completion. (Pamukcu, 2015) noted that risk is inherent all engineering applications. The common practice area of mining and civil engineers, tunnel construction, is also prone to several hazards originating from different sources.

Over the past few years, several risk studies have been conducted at Addis Ababa University. All the studies conducted by (Getachew, 2009), (Addis, 2014), (Getachew Y. , 2014), (Nejbel, 2014), (Temsegen, 2015), (Milka, 2016) and (Emran, 2017) concentrated on the identification of risks affecting building and road construction sectors in Addis Ababa. None of the studies conducted a detailed risk analysis to quantify the impact of the risks identified. Whereas it has been recommended in previous studies, there is currently limited risk study that has been conducted for the railway sector and particularly in relation to tunnels and yet the risk in tunnelling is always the object of attention because of time and cost overruns associated with them.

2.4.2 Risk Assessment Process

The risk assessment process contains the following three steps as identified by (Spackova, 2012): First, identification of phenomena and events, which might influence the stakeholders' objectives in either positive or negative way (risk identification). The process involves determining which risks may affect the project and documenting their characteristics. (PMBOK, 2008). Second, Analysis of the causes and likelihood of the events and their impacts on a qualitative or quantitative basis (risk analysis). Third, comparison of the results of the risk analysis with the acceptance criteria and with the objectives and decisions on how to treat the risks (risk evaluation). However, in a complex environment such as tunnelling, (Spackova, 2012) mathematically modelled the quantitative risk assessment which pertains to observations made in the past which cannot be used for decision making such as delay prediction which requires observations or situations in the present. Similarly, (Pamukcu, 2015) conducted a tunnel risk assessment and prioritization based on severity and event tree analysis which is a mathematical model for risk analysis, but did not analyze the impact of risk occurrence on major aspects of the project such as schedule and cost.

Without providing particular procedure for utilization of discrete event simulation in risk assessment, (Vose, 2002) indicated that the complete risk assessment procedure is likely to consist of five steps:

1. Identification of risk that is to be analyzed
2. A qualitative description of the problem and the risk – why it might occur, what you can do to reduce the risk, probability of the occurrence etc.
3. A quantitative analysis of the risk and the associated risk management options that is available to determine or find an optimal strategy for controlling and hereby solving the risk problem
4. Implementing the approved risk management strategy
5. Communicating the decision and its basis to various decision-makers.

This research includes the first three steps, while the last two are outside the scope of the study.

2.4.3 Risk identification

First principles require that project schedule delay be clearly and directly driven by identified and quantified risks. Primary outputs from identify risks are the initial entries into a risk

register. This risk register should be kept active during the life of the project and updated as risks occur (PMBOK, 2008). In the probabilistic approach, (Spackova, 2012) noted that the risks from the risk register drive the simulation. The report further highlighted the most common means of conducting qualitative risk assessment as, a risk workshop with the engagement of the senior members of the tunnel project team along with key members from the client. However, the document does not indicate the contents of the risk register as well as how to deal with biasness in the risk feedback from stakeholders since they all have interests to protect. However, (PMBOK, 2008) recommends that the biasness be dealt with by establishing definitions of levels of probability and impact. Risk workshops and/or risk interviews provide means of conducting risk identification and the collection of risk data. Devices such as the risk breakdown structure may be used to help participants think of risk that may be outside of their specific assigned area but which they know about (AACE, 2011).

According to (Brox, 2017), many different tools can act as risk registers ranging from comprehensive software suites to simple spreadsheets. A risk register should be designated as a master project document, which upon being created during the early stages of a tunnel project, should be maintained as a live document throughout the life of the tunnel to track risk issues and address problems as they may arise. A typical risk register should contain the following:

- A risk category to group similar risks;
- A brief description or name of the risk to make the risk easy to discuss;
- The probability or likelihood of its occurrence rated on a number scale (e.g. 1-5);
- The impact or consequence should this event actually occur rated on a number scale (e.g.1-5);
- Risk Score or severity (the multiplication of Probability and Impacts)
- Ranking (relative position of importance of all risks).

According to (AACE, 2011), it is recommended that a degree of estimating error be added as an uncertainty to deal with any schedule estimating biases discovered during the workshop/interview process. From risk identification, the risks chosen for the analysis are generally those assessed to be “high” and perhaps some “moderate” risks from the risk register.

Owing to the complexity of risk identification process, the inability to access the actual site risk data and the amount of time available for this research, it was decided that identification of risks be based on previous research in order to develop. Subsequent desk study yielded the following:

Tunnelling risk analysis conducted by (Farid Ghazali and H.C. Wong, 2013) identified 15 tunnelling risks on Malaysian tunnel construction projects with their likely consequences categorized as health and safety, cost overrun and time as indicated in Table 2.4-1 below:

Table 2.4-1 Tunnelling Risks identified by Farid & Wong (2013)

Hazard No.	Consequence	Hazard
1	Health and Safety	1. Confined working area
		2. Dusty and hazardous work environment
		3. Explosives impact
2	Cost Overrun	1. Underestimate cost
		2. Unforeseen event occurrence
		3. Design variation
		4. Economic crisis
		5. Economic inflation
		6. Exchange rate fluctuation
3	Time Overrun	1. Accidents
		2. Labour remonstration
		3. Political change
		4. Stop work order
		5. Delay in material delivery
		6. Plant and machinery failure

A study conducted by (Charoenngam & Yeh, 1999) categorized the risks responsible for time and cost overruns on major construction projects as indicated in Table 2.4-2 below:

Table 2.4-2 Categorization of risks based on Charoenngam & Yeh (1999)

Hazard No.	Category	Hazard
1		Construction delay

Hazard No.	Category	Hazard
	Construction-related risk factors	Changes in the work
		Availability of resources
		Delayed site access
		Late drawings and instructions
		Defective design
		Cost of tests and samples
		Actual quantities of work
		Damage to persons or property
2	Performance-related risk factors	Defective work
		Productivity of equipment
		Productivity of labour
		Conduct hindering work performance
		Suitability of materials
		Labour disputes
		Accidents
3	Contractual and legal risk factors	Delayed dispute resolution
		Change order negotiation
		Delayed payment on contract and extras
		Insolvency of contractor or owner
4	Financial and economic risk factors	Inflation
		Funding
		National and international impacts
5	Political and societal risk factors	Environmental issues
		Regulations (e.g. safety or law)
		Public disorder
6	Physical risk factors	Subsurface geological conditions

Hazard No.	Category	Hazard
		Subsurface hydrogeological conditions
		Acts of God (earthquake, fire etc.)

Another study conducted by (Eskesen, Tengborg, Kampmann, & Veicherts, 2004) suggested a hazard grouping as in Table 2.4-3 below:

Table 2.4-3 Categorization of risks based on Eskesen, Tengborg, Kampmann, & Veicherts (2004)

Hazard No.	Category	Hazard
1	General hazards	Contractual disputes,
		Insolvency and institutional problems,
		Authorities interference,
		Third party interference,
		Labour disputes
2	Specific hazards	Accidental occurrences,
		Unforeseen adverse conditions,
		Inadequate designs, specifications and programmes
		Failure of major equipment
		Substandard, slow or out-of-tolerance works

A study conducted by (Ameh, 2011) identified 18 factors from literature which were chief among the causes of time overrun on construction sites. These factors are indicated in the Table 2.4-4 below:

Table 2.4-4 Categorization of risks based on Ameh (2011)

No.	Time Overrun Factor
1	Inadequate fund for the project
2	Inadequate planning of project before commencement
3	Inadequate tools and equipment

No.	Time Overrun Factor
4	Delay in delivery of materials
5	Design changes during project execution
6	Subcontractor incompetency
7	Delay in response to decision taking
8	Incompleteness of technical documentation
9	Variations
10	Labour dispute in form of strike or lock-out
11	Unexpected subsoil/ground condition
12	Community issues
13	Unclear or inadequate instructions to operators
14	Temporary work stoppages due to adverse weather
15	Delay in inspection and testing of completed work
16	Political instability or change in government policies
17	Accidents
18	Obtaining building permit and approvals

Based on the studies above, Table 2.4-1 to 2.4-4, a summary of the risks involved in tunnel construction was compiled as indicated in the summary Table 2.4-5 below:

Table 2.4-5 summary of the risks involved in tunnel construction based on similar research

Hazard Number	**Hazard**	**Risk consequence**					
		Financial	Schedule	Reputation	Health and Safety	Regulatory or Legal	Environment
1	Underestimate cost						
2	Unforeseen event occurrence						
3	Design variation						
4	Economic crisis						
5	Economic inflation						
6	Exchange rate fluctuation						
7	Funding						
8	Cost of tests and samples						
9	Actual quantities of work						
10	Accidents						
11	Labour remonstration/ disputes						
12	Political change						
13	Defective work						

Hazard Number	Hazard	Risk consequence					
		Financial	Schedule	Reputation	Health and Safety	Regulatory or Legal	Environment
14	Delay in material delivery						
15	Plant and machinery failure/productivity						
16	Manual tasks/ Labour productivity						
17	Subsurface geological conditions						
18	Subsurface hydrogeological conditions						
19	Acts of God (earthquake, fire etc.)						
20	Delayed dispute resolution						
21	Change order negotiation						
22	Delayed payment on contract and extras						
23	Late drawings and instructions						
24	Delayed site access						
25	Insolvency of contractor or owner						
26	Confined working area						
27	Dusty and hazardous work environment						
28	Explosives impact						
29	Noise						

Hazard Number	Hazard	Risk consequence					
		Financial	Schedule	Reputation	Health and Safety	Regulatory or Legal	Environment
30	Heat Stress				■		
31	Loss of lighting				■		
32	Rock falls, Failure of floor or roadway, Scaling, High water and mud inflow, Gas inrush, Falls from height etc due to ground nature	■			■		
33	Poor safety culture	■		■	■		
34	Regulations (e.g. safety and environmental laws)					■	
35	Environmental issues						■
36	Public disorder						■

2.4.4 Qualitative Risk Analysis

Qualitative risk analysis is the process of prioritizing identified risks for the project in question by action of assessing their probability and impact (AACE, 2011), (PMBOK, 2008). The result of risk prioritization is to group the identified risks into high risk, moderate risk and low risk separately for the schedule and cost. These form the basis of the quantitative risk data collection for the risk analysis of the schedule (PMBOK, 2008). This assessment mainly reflects the attitude towards risk of the project team and other stakeholders at risk. Effective assessment requires identification and management of risk attitudes of key participants in the Qualitative risk assessment process.

Qualitative risk analysis can be conducted using the following tools and techniques as recommended by (PMBOK, 2008)

- **Risk Probability and Impact Assessment:** The probability assessment involves estimating the likelihood of a risk occurring. The impact assessment estimates the effects of a risk event on a project objective such as schedule, cost, time etc. Probabilities and Impacts are assessed for each identified risk. This assessment can be conducted in meetings or interviews with participants selected for their expertise in the area under assessment. The risk probabilities and impacts are rated according the pre-defined scales. Those risks that rate highest after the analysis are included on the future watch list.
- **Probability and Impact Matrix:** Risks can be prioritized for further quantitative analysis and planning risk responses based on their risk rating. Ratings are assigned to risks based on their assessed probability and impact. Evaluation of each risk's importance and priority for attention is typically conducted using a probability and impact matrix. Such a matrix specifies combinations of probability and impact that lead to rating the risks as low (Green zone), moderate (Yellow zone), or high priority (Red Zone) as in Figure 2.4-1. Descriptive terms or numeric values can be used depending on organizational preference.

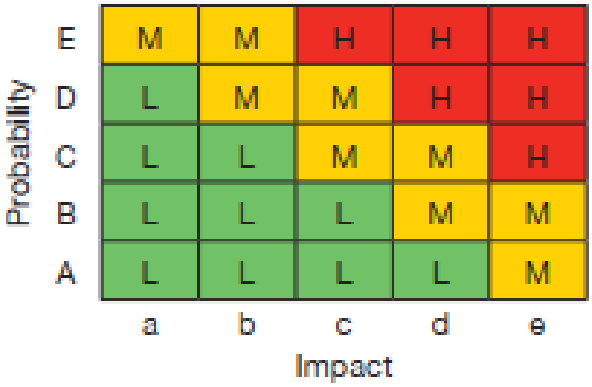


Figure 2.4-1 Heat map

Each risk is rated on its probability of occurrence and impact on an objective if it does occur. A project should define which combinations of probability and impact result in a classification of high risk, moderate risk, and low risk. Usually, these risk-rating rules are specified by a project in advance and included in project process assets separately for each project objective (e.g., cost, time, and scope).

The risk score helps guide risk responses. For example, risks that have a negative impact on objectives, otherwise known as threats if they occur, and that are in the red zone of the matrix, may require priority action and aggressive response strategies. Threats found in the low-risk zone may not require proactive management action beyond being placed in the risk register as part of the watch list or adding a contingency reserve.

It should be noted that the accuracy of the results from the analysis depends on the level of experience of the assessors. Incase the risk assessors lack sufficient experience with a particular identified risk, the qualitative analysis results will be incorrect.

2.4.5 Quantitative Risk Analysis

Quantitative risk analysis as a further analysis of the highest priority risks including the assignment of a numerical or quantitative rating in order to develop a probabilistic analysis of the project (Pamukcu, 2015).

A quantitative analysis:

- Quantifies the possible outcomes for the project and assesses the probability of achieving specific project objectives.
- Provides a quantitative approach to making decisions when there is uncertainty.

- Creates realistic and achievable cost, schedule or scope targets.

Quantitative risk analysis should be considered under the following circumstances: projects that require a Contingency Reserve for the schedule and budget; for large, complex projects that require Go/No Go decisions (the Go/No Go decision may occur multiple times in a project), and projects where upper management wants more detail about the probability of completing the project on schedule and within budget.

The advantage of using Quantitative Risk Analysis is that instead of only creating a number of possible scenarios it effectively accounts for every possible value that each variable within the model can take by use of various continuous probability distributions (Salling).

Quantitative Risk Analysis and Modelling Techniques are used by project managers to determine level of influence of the risks identified. These techniques include but not limited to probability distribution, data gathering and representation techniques, sensitivity analysis, Expected Monetary Value analysis, Event Tree Analysis, decision tree analysis, tornado diagrams and Severity Risk Analysis. It also uses modeling and simulation which is an important technique in quantitative risk analysis. A good simulation technique used by project managers is the Monte Carlo analysis which is calculated using the computer and analyzing different scenarios for the project schedule to identify possible risk events and Discrete Event Simulation (Eskesen, Tengborg, Kampmann, & Veicherts, 2004), (PMBOK, 2008). Some of the techniques and their applicability are discussed in Table 2.4-6 below.

Table 2.4-6 Quantitative Risk Analysis Techniques (PMBOK, 2008)

#	QUANTITATIVE RISK ANALYSIS TECHNIQUE	APPLICABILITY
1.	Severity Risk Analysis	This has become the standard method in establishing risk severity in Qualitative Risk Analysis. Risk Matrices will often vary in size, but they all essentially do the same thing, and that is: Provide a practical means of ranking the overall severity of a risk by multiplying the likelihood of risk occurrence against the impact of the risk, should it still occur. Through ranking risk probability against risk consequence, one is able to not only determine the overall severity of the risk, but also determine the main driver of the risk severity, be it probability or consequence. This information is then useful in helping identify suitable mitigations to manage the risk, based on its prominent drivers.
2.	Sensitivity Analysis	Used to determine which risks have the most potential impact on the project. Sensitivity analysis examines the extent to which variation of a project element affects a project objective when all other uncertain elements are held at their baseline values.
3.	Expected Monetary Value analysis	Is a specific analytical technique in which a calculation is made to determine the average of all potential outcomes when the future includes a number of particular scenarios that may or may not ultimately happen. These scenarios can all be interpreted as potential happening individually, or they may happen in varying multitudes. One common utilization of this technique takes place within a technique such as decision tree analysis. It is also recommended that a project team utilize simulations and modeling when conducting a cost and/or a schedule risk analysis because it is

		in reality significantly more powerful and is typically subject to less erroneous application than other analytical methods such as monetary value analysis. The expected monetary value analysis, which also can be referred to by the anagram EMV. Can be conducted at any point in the life cycle of a project but should be done as early as possible.
4.	Decision Tree Analysis	Similar to Event Tree Analysis, but without providing a fully quantitative output, Decision Tree Analysis is most often used to help determine the best course of action wherever there is uncertainty in the outcome of possible events or proposed plans. This is done by starting with the initial proposed decision and mapping the different pathways and outcomes as a result of events occurring from the initial decision. Once all pathways and outcomes have been established, and their respective probabilities evaluated, a course of action may be selected based on a combination of the most desirable outcomes, associated events and probability of success.
5.	Modelling and Simulation	A project simulation uses a model that translates the uncertainties specified at a detailed level into their potential impact on objectives at the level of the total project. Project simulations are typically performed using the Monte Carlo technique as well as Discrete Event Simulations. For a cost risk analysis, a simulation may use the traditional project WBS as its model. For a schedule risk analysis, the Critical Path Method (CPM) schedule is used. The outcome of simulation illustrates a specific likelihood of achieving a particular target with respect to schedule or cost. A paper by (Shannon, 1992) divided typical simulation objectives into the following: Sensitivity Analysis, Scheduling, Prediction, Optimisation, Functional Relations, Evaluation, Comparison and

		Bottleneck Analysis. Objectives from the construction case studies normally include; optimising resource configurations (*Sensitivity Analysis*); determining construction completion times (*Prediction*); feasibility study prior to purchasing a piece of machinery (*Evaluation*); arbitration over costs involved with design changes (*Comparison*); planning of the operations in house construction (*Scheduling*). This implies that matches in problems and objectives do exist between manufacturing and construction, and simulation has the capability of being used as a decision support tool when planning in construction.

It is important to note that whereas many studies have been conducted around the application of most risk modelling techniques including Monte Carlo Simulation, only a limited number of studies have been made to utilize the capabilities of discrete event simulation in quantifying time and productivity-related impacts. These studies are demonstrated in the works of (AbouRizk & Dozzi, 1993) and (Vanegas & Halpin, 1993). The study by (AbouRizk & Dozzi, 1993) simulated two scenarios; first is a model of an operation based on the construction method specified in the contract (As-planned) and the second model simulated the actual operation (As-built). The durations (in terms of man-hour) required to complete the two models were used as a basis to estimate the reasonable range of cost to be awarded to the contractor. On the other hand, (Vanegas & Halpin, 1993) indicated that simulation could be used as a preventive tool in the planning stage and as a tool to resolve disputes. The utilization of the Record modules in simulation software allows easily for tracking these time changes at specific points in the model, thus enabling for the building of the Base model as an ABM to be used in the prediction of delays due to occurrence of risks.

2.4.6 Risk Analysis Practice in Ethiopia

Over the past few years, several risk studies have been conducted in Ethiopia. The studies conducted by (Getachew, 2009), (Addis, 2014), (Getachew Y. , 2014), (Nejbel, 2014), (Temsegen, 2015), (Milka, 2016) and (Emran, 2017) concentrated on the identification of risks affecting the building and road construction sectors in Addis Ababa. None of the studies conducted a detailed risk analysis to quantify the risks identified. There is currently no risk study that has been conducted for the railway sector as recommended by previous studies and particularly none in relation to tunnels and yet the risk in tunnelling is always the object of attention because of time and cost overruns associated with them.

2.4.7 Risk Correlations

As part of the risk assessment, risk dependencies, interdependencies, and the timeframe of the potential impact need to be identified. Decisions can be based on either single or multiple criteria. Usually, it is simpler to come to a conclusion on decisions when it involves just one measure. However, in project management, schedule delay due to occurrence of risks does not deal with one but many criteria. It is rather complex when it comes to decision making in real schedule analysis as one decision will affect not only one operation or practice but will also lead to another. This occurrence is called as multi-criteria decision making (MCDM); where we have finite number of criteria on infinite number of alternatives (Steuer, 1986).

There various MCDM methods that have been used in practice some of which include; Analytic Hierarchy Process (AHP), Elimination and Choice Expressing Reality (ELECTRE), Goal Programming (GP), Multi-attribute Value Theory (MAVT), Analytic Network Process (ANP), Multi-attribute Utility Theory (MAUT), and Decision Making Trial and Evaluation Laboratory (DEMATEL) (Ali, Sorooshian, & Kie, 2016). For this research, we shall concentrate on DEMATEL as our method of choice. This is a popular method, which enables an analysis of cause-and-effect relationships between risks to project objectives.

DEMATEL Method

DEMATEL forms as a comprehensive method where the causal relationship of the criteria can be constructed into a structural model and analyzed further. DEMATEL has demonstrated to be a good and effective MCDM in many applications such as control systems, project management, strategies, operations management and et-cetera. (Ali, Sorooshian, & Kie, 2016). It has the ability to solve complex problems by enabling the understanding of complicatedly

interacted factors and criteria. In other words, DEMATEL can be used employed to construct an Impact-Relation Map (IRM) as well as to identify and realize the influence levels of each elements over the other (Fontela & Gabus, 1974). By knowing the nature and degree of influence an attribute or criterion has on each other, the reflection on the system's characteristics could be comprehended (Amiri, Sadaghiyani, Payani, & Shafieezadeh, 2011).

The methodology can confirm the interrelations among the variables/attributes and also obtain the influence levels of each variable over others. The end product of the DEMATEL process is a visual representation-an individual map of the mind-by which the respondent organizes his or her own action in the world (Amiri M. , 2011).

CHAPTER 3: RESEARCH DESIGN & METHODOLOGY

3.1 Introduction

The previous chapter discussed literature relating to tunnelling risk and uncertainties, Risk identification methods, Risk Modelling, and the various methods involved in Risk Analysis to be used in Delay prediction such as Qualitative Risk Analysis, DEMATEL Analysis, Severity Analysis, Monte Carlo Simulation, and Discrete Event Simulation (DES).

This Chapter deals with materials and methodology of the research. In designing the research method; types of research, research strategy, research approach, data collection and analysis methods that were applied.

3.2 Research Design

The research strategy adapted for this research was mixed methods which incorporate elements of both qualitative and quantitative approaches. This involved collecting both quantitative and qualitative data, integrating the two forms of data and using distinct designs that involved philosophical assumptions and theoretical frameworks. The overall approach, as indicated in Figure 1.6-1 included in Chapter 1 of this thesis, followed a five stage process; having established the basis of the research through literature review, necessary data was collected, analyzed, and conclusions and recommendations were made based on the findings. The methods of data collections employed for the research were case study, desk study, and interviews with tunnelling experts. The case study and desk study were analyzed in relation to theoretical propositions, and the responses obtained from the interview were also analyzed using descriptive statistics method. The next sections discuss the tools used for data collection and method of analysis.

3.3 Desk Study

3.3.1 Risk Identification

Data required for Risk identification for tunnel construction by drill and blast tunnelling method was based on desk study of past research around the world relating to conventional drill and blast

tunnelling to produce a risk register. In the risk register categorized the hazards and their consequences due to occurrence (financial, schedule, reputation, health and safety, Regulatory/Legal, and environmental). This ultimately enabled the identification of schedule risks necessary for the inclusion in the interview questionnaire.

3.3.2 Description of the Case Study Area

Two key research methods, namely case study and semi-structured interviews were used to identify significant risks and sub-risks for tunnelling construction projects in Ethiopia. Some identified tunnelling projects in Ethiopia have been completed and are now under operation while some are still undergoing construction. Amongst the railway tunnelling projects identified include Menelik II Tunnel and Tunnel 1-14 of the Awash-Kombolcha-Hara-Gebeya Railway Project.

The case study was based on an actual project, Awash - Kombolcha – Hara Gebeya Railway Project tunnel construction (see Figure 3.3-1 for project alignment and Figure 3.3-2 for Tunnel 3) being undertaken on behalf of Ethiopian Railway Corporation. The delay prediction due to risk occurrence was that taking place during the Construction phase of the project. The risk analysis team comprised of the researcher (Joy Kirinda) working closely with the EPC Contractor's team as well as the Supervision Consultant to complete the delay prediction due to risk occurrence.

The project under consideration is a single-track railway line of total length 389km when completed with a maximum design speed of 120 km/h for passenger and 80 km/h for freight to be constructed over the original construction period of 66 months. The Project major civil works include 94.7 million m^3 of Earthworks, 12 pieces of Tunnels (originally 14) with total length of 9,830 m, 51 pieces of Bridges with total length of 5,897 m, 14pieces of Overpasses with total length of 1,268 m, 917 pieces of Culverts with total length of 41.0 km, 426 km of Track works.

The project team is led by EPC Contractor Yapı Merkezi İnşaat ve Sanayi A.Ş. working with Systra AB in Consortium with Multi-D Engineering Consultancy Plc. The main contractor has also successfully completed the Dubai Metro Project, Casablanca tramline and Ankara – Konya high-speed rail line, which make Yapi Merkezi a world brand in rail systems. The site personnel include 8,577 people working in Ethiopia on the Awash - Kombolcha – Hara-Gebeya Railway Project of whom 2,817 are Turkish & other Expatriates (445 white collar and 2,372 Blue Collar) and 5,760 Ethiopians (200 White Collar and 5,560 Blue Collar).

Project owner Ethiopian Railway Corporation (ERC) is investing $1.7bn in the project. Construction of the new line commenced in February 2015 and was expected to be completed in 2017. However, due to occurrence of certain hazards, the construction works have experienced a delay in schedule.

Tunnel construction has consumed the biggest single item cost of the project's budget with the remaining budget associated with the rest of the works. These tunnels have been constructed using the conventional tunnelling method (Drill and Blast with Bench cut)

The project was meant to be completed within a pre-established budget that was determined at concept design and approved by ERC as well as the approved construction period of 66 months.

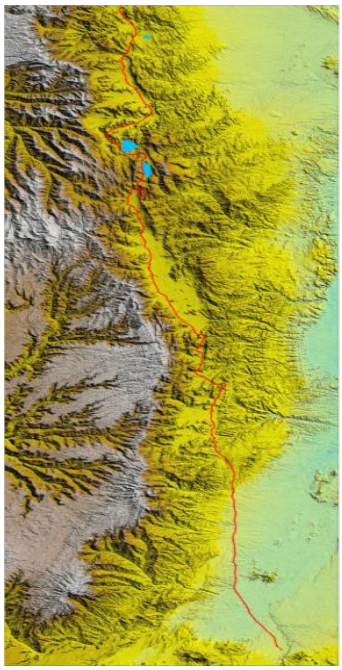


Figure 3.3-1 Project Alignment (Adopted from the Awash -Kombolcha -Hara Gebeya Railway Project summary and status report for December 2017)



Figure 3.3-2 Tunnel 3 for Awash -Kombolcha -Hara Gebeya Railway Project

3.4 Data Collection

3.4.1 Primary Data

The source of the primary data was collected through conducting interviews in form of a questionnaire (See Appendix 1), designed to gather a large volume of risk data from consultant's and contractor's tunnel experts on Awash-Kombolcha railway project. The primary function of the survey was to collect information that can be analyzed, and inference made to produce conclusion about major schedule risk factors in the conventional drill and blast tunnelling. The primary data collected included the likelihood of occurrence of risk and their consequences, the interrelations between risks and three-point estimates of each activity in a tunnelling cycle. The interviews involved speaking to tunnel experts at each location, talking through each hypothetical risk on the list to get their estimate of frequency, consequence, interrelations and durations. Frequency was reported in terms of probability of occurrence of a particular risk event, consequence in terms of severity, interrelations in the form of a pre-defined scale while duration was reported using a triangular distribution due to its intuitive nature (the experts estimated the minimum, most likely, and maximum time they could imagine a disruption lasting at their facility).

Estimates were obtained from both the Consultant and Contractor's tunnelling experts in order to validate the data obtained and rule out biasness.

3.4.2 Secondary Data

Secondary data involved information from site documents, research journals, government publications, internet sources were used to compliment the primary data. The secondary data obtained from site included the As- Planned and As-Built tunnelling schedules, tunnel lengths and location.

3.5 Analysis and Results Methodology

Analysis involved applying the various qualitative (risk prioritization) and quantitative risk analysis (DEMATEL, Severity, Monte Carlo Simulation and Discrete Event Simulation) to determine the project delay.

3.5.1 Qualitative Risk Assessment

Based on the frequency and consequence results (risk prioritization) from the interviews, a qualitative analysis was conducted using pre-defined inference table in Appendix 2. This was aimed at making conclusions on whether a particular hazard was Intolerable, critical, serious, important, acceptable or negligible.

This would eventually provide an idea of the major risks that affect tunnelling schedule which are of main interest.

3.5.2 Risk Correlations and Interrelations

Risk Correlation analysis was conducted to determine how the occurrence on one risk affects another. Since this was carried out using DEMATEL analysis summarized in Figure 3.5-1 and described below. It is stated in (PMBOK, 2008) 'Projects can improve their performance by focusing on high priority risks'. Consequently, only the 'intolerable' risks from Severity analysis would be considered for DEMATEL analysis.

DEMATEL analysis

STEP 1: Gather Expert's Opinion and Calculate the Average Matrix *Z*

Let's consider a group of *m* experts and *n* factors for this study. Experts were given a list of factors arranged in sets of *i* and *j*. They were then asked to indicate the degree of direct influence each factor (element) *i* exerts on each factor/element *j*, which is denoted by *x*ij (pair-wise comparison); how does factor *i* affects factor *j*. The indication was made on the scale of 0-3; 0 = no influence, 1 = weak direct influence, 2 = moderate direct influence, 3 = strong direct influence.

For each expert, an *n x n* non-negative matrix was constructed as $\boldsymbol{X}_k = [x_{kij}]$, where *k* is the expert number of participating in the evaluation process with $1 \leq k \leq$ m. The mathematical notation can be formulated as below:

$$X = \begin{bmatrix} 0 & x_{12} & \cdots & x_{1n} \\ x_{21} & 0 & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & 0 \end{bmatrix}$$

Thus, we had X^1, X^2, X^3…… X^m as the answer matrix obtained from the experts. Each element of the matrices was denoted with x_{ij} representing the degree of impact *i* has on factor *j*. The diagonal elements of each matrix were set to zero as DEMATEL does not evaluate self-influence of factors. An average understanding on the experts' response had to be reached was done by calculating the average of the matrix which was called as an initial direct-relation matrix. This matrix was presented as matrix $\boldsymbol{Z} = [z_{ij}]$ in Equation 3.5-1 below. (Ali, Sorooshian, & Kie, 2016):

$$Z_{ij} = \frac{1}{m}\sum_{i=1}^{m} x_{ij}^{k} \qquad \text{……Equation 3.5-1}$$

STEP 2: Normalizing the Initial Direct-Relation Matrix *D*

Normalized direct relation matrix ***D*** then was calculated from the average matrix ***Z***. This was done by dividing each element by the largest row sum of the average matrix. Total direct influence on the influence scale of the factor with most direct influence on the other factors was represented as factor

$$s = max_{1 \le i \le n} \sum_{j=1}^{n} z_{ij} \qquad \text{……Equation 3.5-2}$$

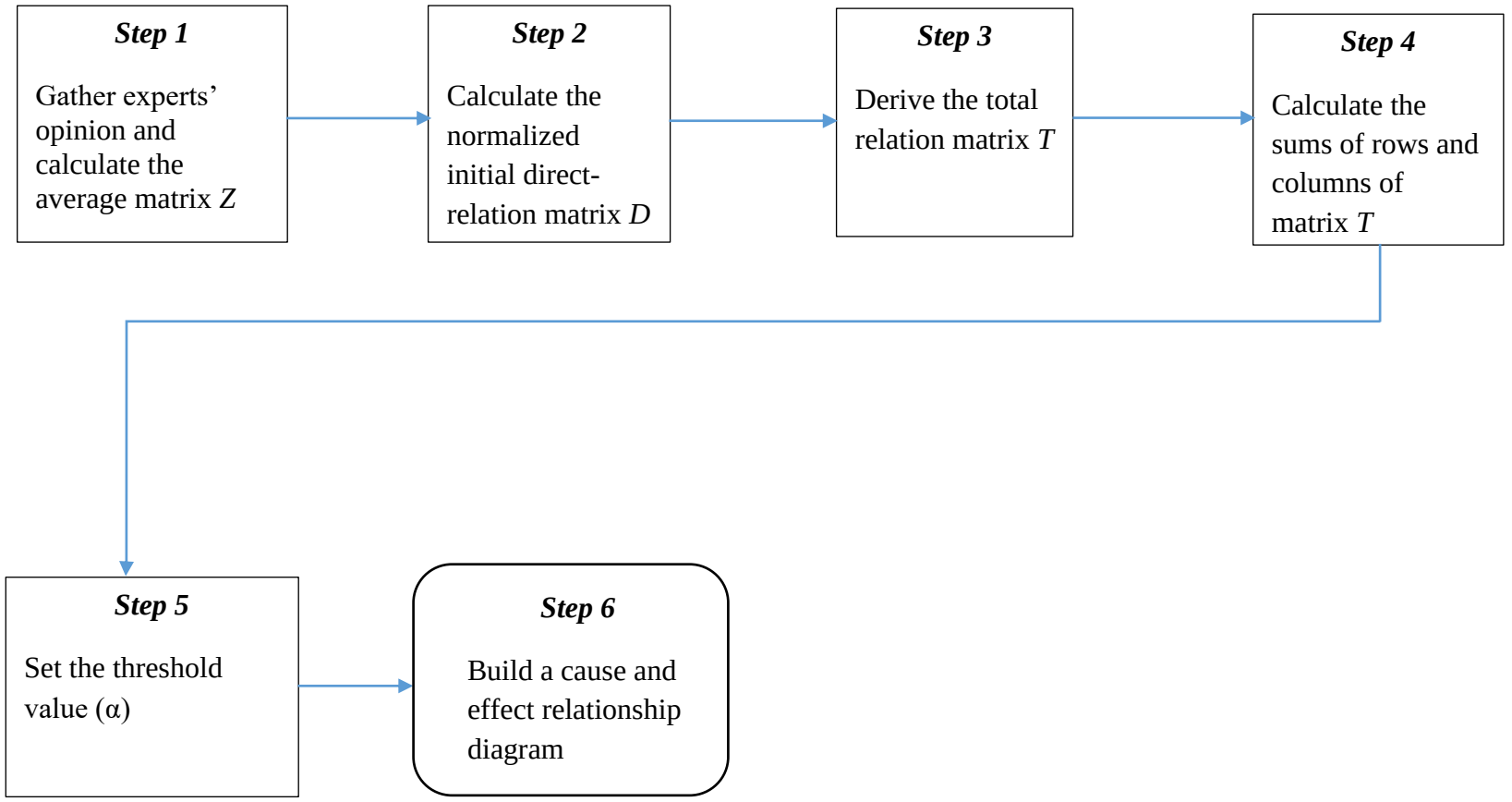


Figure 3.5-1 Summary of DEMATEL Procedure

The value of each element in this normalized direct-relation matrix ***D*** was to range between [0, 1]. The calculation to obtain the meant matrix was as shown:

$$D = \frac{Z}{s}$$

……*Equation 3.5-3*

STEP 3: Obtaining the Total Relation Matrix *T*

Employing this step would realize the direct/indirect or total relationship between each pair of the system factors. The elements t_{ij} in matrix T represents the indirect effects that factor *i* had on factor *j* and then the matrix T reflects the total relationship between each pair of system factors. The assumptions are that the indirect influence matrix converges to the null matrix as shown below:

$$\lim_{k\to\infty} D^k = 0$$

……*Equation 3.5-4*

Where 0 is the null matrix with I is an n x n identity matrix, the following hold true:

$$\lim_{k\to\infty}(I + D + D^2 + \cdots + D^k) = (I - D)^{-1}$$

……*Equation 3.5-5*

The total relation matrix *T* is, therefore, defined as:

$$T = D(I - D)^{-1}$$

……*Equation 3.5-6*

STEP 4: Computing Sums of Rows and Columns of Matrix T

Vector R and D were to present the sum of rows and sum of columns respective in the total-influence matrix ***T.*** Let vector R be *n* x 1 and D be 1 x *n.* Thus, the sum of row were calculated as:

$$(D_1 \ldots\ldots D_n) \quad \text{with} \quad D_j = \sum_{i=1}^{n} t_{ij} \quad \text{where} \quad (j = 1,2,3 \ldots\ldots n)$$

...*Equation 3.5-7*

The sum of column on the other hand were calculated as follows:

$$\begin{bmatrix} D_1 \\ : \\ D_n \end{bmatrix} \text{ with } D_i = \sum_{j=1}^{n} t_{ij} \text{ where } (i = 1,2,\dots,n)$$ ……*Equation 3.5-8*

It summarized both the direct and indirect effects that factor *i* exerts on the other factors. Similarly, if R*j* was the sum of the *j*th column in the matrix ***T***, then:

$$\begin{bmatrix} D_1 \\ : \\ D_n \end{bmatrix} \text{ with } D_i = \sum_{j=1}^{n} t_{ij} \text{ where } (i = 1,2,\dots,n)$$ ……*Equation 3.5-9*

It summarized the direct and indirect effects that factor *j* receive from the other factors. When *i* = *j*, the sum (D*i* + R*i*) showed the total effects given and received by factor *i*, thus:

$$(D_i + R_i) = \sum_{j=1}^{n} t_{ij} + \sum_{k=1}^{n} t_{ik}$$

$$(D_i + R_i) = \sum_{j=1}^{n} t_{ij} + \sum_{k=1}^{n} t_{ik}$$ ……*Equation 3.5-10*

It represented the degree of importance of factor *i* in the entire system. The difference indicates the net effects that factor *i* contributes to the system and is shown below:

$$(D_i - R_i) = \sum_{j=1}^{n} t_{ij} - \sum_{k=1}^{n} t_{ik}$$ ……*Equation 3.5-11*

Specifically, if (D_i – R_i) was found to be positive, the influence factor *i* was deduced as a net cause, while if (D_i – R_i) was negative, factor *i* was a net receiver.

STEP 5: Setting the Threshold Value, α

Since Matrix T provides information on how one factor affects another, it is necessary for a decision maker to set up a threshold value to filter out some minor effects. In doing so, only the effects greater than the threshold value, would be chosen and shown in digraph. In practice, the threshold value is set up by computing the average of the elements in matrix T as such:

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}[t_{ij}]}{N}$$

……*Equation 3.5-12*

Where ***N*** is the total number of elements in matrix ***T***

STEP 6: Building the Impact-Relation Map

As mentioned earlier, DEMATEL in the last effort would be producing an Impact Relation Map (IRM). This was constructed by mapping all coordinate sets of ($D_i + R_i$, $D_i - R_i$) to visualize the complex interrelationship. This diagram was to provide information to the researcher on which are the most important factors and the influence (Shieh, Wu, & Huang, 2010). The factors that T_{ij} is greater than α are selected and shown in cause and effect diagram (1RM).

3.5.3 Severity Analysis

From the data collected, using Pre-defined scales, According to (AbouRizk S. M., 2008), to quantify risk factors based on severity the following process was used:

1. Converting the frequencies/likelihoods and consequences into quantities based on pre-defined tables in Appendix 4-A
2. Determination of the overall severity of the factor by multiplying the likelihood (1) by magnitude (2).

   Severity = likelihood of occurrence of a risk X magnitude of impact

3. The factors were then grouped based on the overall severity score according to the grouping in the table in Appendix 4-B.
4. Based on the results of the severity analysis, categorization of the schedule risks was undertaken as indicated in the table in Appendix 4-C:
5. Schedule delay due to risk occurrence was determined based on Table in Appendix 4-C.

3.5.4 Monte Carlo Simulation

Monte Carlo simulation (MCS), or probability simulation, was another technique used to study the impact of risk and uncertainty on schedule delay.

Inputs to the analysis

- A schedule following recommended practice CPM scheduling.
- Good quality risk data (in terms of minimum and maximum activity durations) that is specific to the project being modelled.

Monte Carlo Simulation Steps

1. Obtaining a CPM Construction Schedule from site from which the 'Most Likely' durations for each activity will be obtained. To create a CPM Schedule for a drill and blast tunnelling cycle, all the activities involved in the execution were identified as in Table 3.5-1 below:

Table 3.5-1 Drill and Blast cycle tunnelling activities

No.	Main Activity	Sub-activities	Description
1	Drilling	Placing drill jumbo	Involves placing the drill jumbos at the tunnel face from its starting position
2		Drilling	Drilling holes at the face of the tunnel using drill jumbos
3		Displacing drill jumbo	Drill jumbo gets displaced from the face of the tunnel to its starting position
4		Repair	Repairing the drill jumbo in case of breakdown
5	Blasting	Loading explosives	Placing the explosives in the drilled holes using platform trucks
6		Blasting	Blasting the tunnel
7	Ventilation	Ventilation	Ventilating the tunnel
8	Mucking	Maneuver truck	Maneuvering the trucks at the face of the tunnel

No.	Main Activity	Sub-activities	Description
9		Load soil	Loading soil in the trucks by a loader
10		Transfer soil	Transporting the soil towards the soil disposal area by trucks
11		Unload soil	Unloading the soil from the trucks at the soil disposal area
12		Return empty truck	Empty truck returns to its starting position
13		Stop soil disposal	Soil disposal cycle is finished
14	Scaling	Mechanical scaling	Scaling mechanically along the surface area of the excavated tunnel with an excavator
15		Manual scaling	Scaling the excavated tunnel manually with the use of platform trucks
16	Shotcrete	Shotcreting	Spraying concrete onto a surface at high velocity to achieve high strengths using shotcrete gun
17	Final lining and ground support	Transfer lining material	Transporting lining materials (rock bolts and wire mesh) towards the face of the tunnel
18		Unload lining material	Unloading the lining material at the heading of the tunnel
19		Return empty material truck	Returning of material truck towards its starting position
20		Rock Bolting Tunnel (primary support)	Lining of the tunnel with the use of drill jumbo to drill holes for the installation of rock bolts, and platform trucks

No.	Main Activity	Sub-activities	Description
21	Surveying	Surveying tunnel	Surveying the face of the tunnel to evaluate its position, and determine the position of the holes to be drilled in next construction cycle

All these activities have a finish to start relation. To complete an entire tunnel, the cycles are repeated

2. Debugging the schedule. (The schedule needs to follow CPM scheduling recommended practices because it needs to calculate the milestone dates and critical paths correctly, both in the static critical path method (CPM) schedule and during Monte Carlo simulation).
3. Obtain the Minimum and Maximum expected durations from Expert Opinion (Site Interviews) as per the pre-designed questionnaire.
4. Using the Triangular distribution to generate random values based on a Minimum, Most Likely, and Maximum durations, in the Monte Carlo simulation using @RISK MS-Excel Add-In, values for each of the tasks will be randomly generated, and subsequently the total time to completion calculated. The simulation will be run 5,000 times. Based on the results of the simulation, some of the characteristics of the risk in the model will described.
5. Comparison of Most Likely Duration from Monte Carlo Simulation results with original CPM Construction Schedule to predict the most likely delay will be carried out.

Steps in Monte Carlo Simulation are summarized in Figure 3.5-2 below:

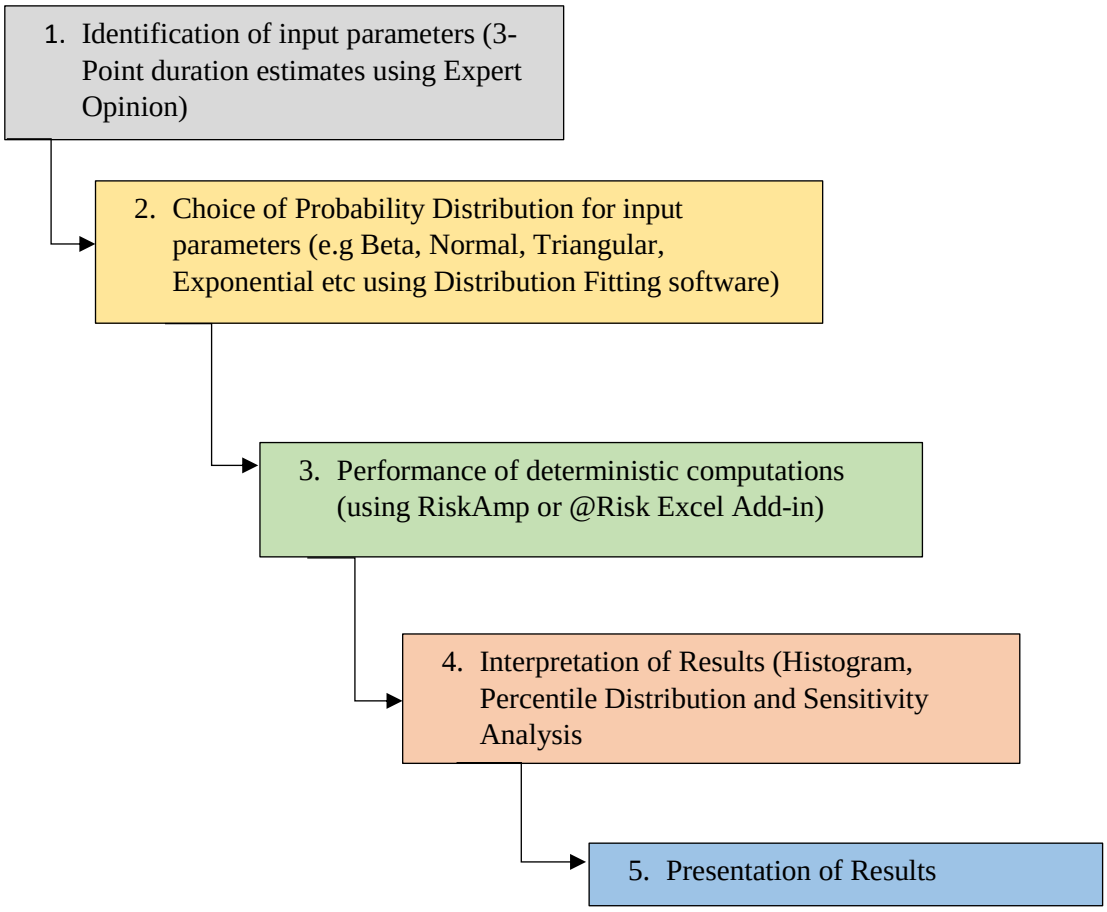


Figure 3.5-2 Procedure for Monte Carlo Simulation

The Risk Profile parameters output by the Monte Carlo simulation shall form inputs for the Arena Risk Simulation Model to be used under Discrete Event Simulation.

3.5.5 Discrete Event Simulation (DES)

Computer simulation provides an environment for decision makers in which they can study the performance of a particular system (in our case time analysis) in a low-cost environment through conducting sensitivity analyses.

In this research, the simulation software, Arena 15.1 was employed to build the simulation model of a construction process. Arena 15.1 has a powerful graphical interface and consists of template modules that are constructed around SIMAN language and is good for predicting

system performance based on key metrics such as costs, throughput, cycle times, and utilizations

The methodology applied in this section is as summarized in Figure 3.5-3 below:

Problem formulation

Problem formulation included problem definition and establishing the project objectives so as to describe what the model output would be. The main objective of this modelling is to develop a drill and blast tunnelling cycle simulation that can be used to assess the impact of risk occurrence on the cycle completion schedule. The model should be able to give an indication of the time it would take to complete a tunnelling cycle when the probability of occurrence of the risks is varied.

Project Planning

Project planning will include scheduling tasks of the simulation project and assigning roles and responsibilities. The tasks under this simulation included model conceptualization, data collection and analysis, model translation, model verification, model validation, experimental design, production of runs and analysis and finally documentation and reporting. These were to be enabled by inputs from the researcher as well as expert knowledge.

Model Conceptualization

Model Conceptualization (System definition): this included the identification of the system components to be modelled, input data, system processes and output measures of performance. This began with the development of a process map indicating activities in one cycle of the drill and blast tunnelling including their sequences and flow of the work. Due to limitations in model size, from Severity Analysis, only the schedule risks which were assessed as intolerable were identified for inclusion in the process map as decision points. The activities involved in a tunnelling cycle were to be represented as processes, while the risks to be assessed as decision modules and the tunnelling cycle as an entity that runs through the system. The model to be built would take into consideration the correlations between risk occurrences and the probabilities of occurrence. The expected output from the model was the time required to complete one tunnelling cycle given the risk occurrences.

Data Collection and analysis

This stage required the collection of data relating to durations of activities in a drill and blast tunnelling cycle. This data would then be used to determine the distribution as well as obtaining random data for use in the ARENA 15.1 Simulation. However, this process had already been undertaken under MCS.

Model Translation

Involved selecting the appropriate simulation software and building the model. The software of choice was ARENA simulation software due to its ease of use without a requirement for learning code language. The Entities in our case were the tunnelling cycles, and the processes were the tunnelling activities. The risks under study were included as Decision points. The model was developed using the ARENA Basic simulation modules.

Model verification

This was conducted to ensure that the model operates as intended. The model processes were to represent a finish to start relationship. This was done by running a single animated entity several times and observing its flow through the system for any interruptions or inconsistences with reality amidst risk occurrences.

Model validation

To ensure that the model represented reality, parameter variability (Sensitivity Analysis) method was applied. This technique consisted of changing the values of the risk input parameters of the model to determine the effect of output on the model's behavior. The same relations should occur in the model as in the real system. Risk parameters that were considered sensitive (i.e., cause significant changes in the model's behavior or output) were made sufficiently accurate prior to using the model by applying the correlations/weights obtained from DEMATEL Analysis.

Experimental Design

Experimental design will determine which model alternative will be beneficial to investigate.

STEPS IN DISCRETE EVENT SIMULATION (DES)

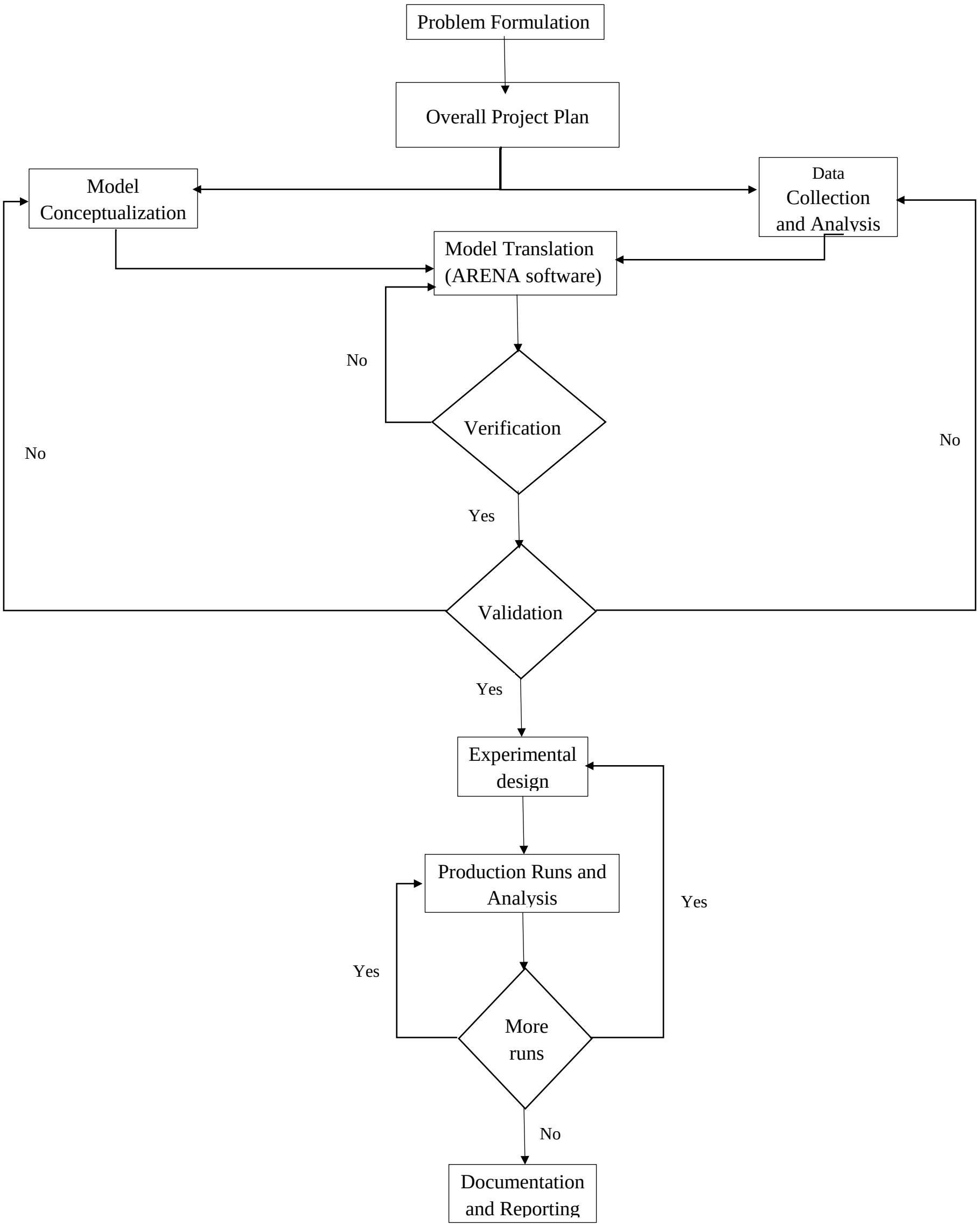


Figure 3.5-3 Steps in Discrete Event Simulation

Production runs and Analysis

Analysis will include statistical comparisons between alternatives.

Documentation and Reporting

Presenting conclusion and results will involve reporting the simulation results regarding the total time required to execute the project amidst the risk occurrences.

3.6 Comparative Analysis

Comparison of results from As-Built CPM Schedule, Severity Analysis, Monte Carlo Simulation and Discrete Event Simulation was conducted using a side-by-side approach

CHAPTER 4: ANALYSIS AND RESULTS

4.1 Introduction

Risk analysis, being a proactive operation is very crucial for the mitigation of risks in tunnel construction for timely project delivery. This Chapter describes how the various risk analysis methods are used to determine drill and blast tunnelling risk.

4.2 Analysis and Results

Following the categorization, the risks with time overrun consequences were selected for frequency and consequence analysis using interviews for Awash-Kombolcha-Heregebeya Project.

Owing to the confidentially of the risk data which is currently also being used as part of the claims, the names of the persons interviewed are withheld and will simply be referred to as Contractor (includes Expert 1, 2 and 3) and Consultant (Expert 4 and 5).

4.2.1 Demographic information

Out of the available eight (8) tunnelling experts from both the Contractor and Consultant on Awash- Kombolcha Project, following simple probabilistic sampling, only five (5) were willing to participate in this survey. This survey was conducted by asking the questions in the pre-designed questionnaire. The number of valid questionnaires is 5. The demographic information of these 5 experts is summarized in Table 4.2-1 below. The demographic information of the respondents.

Table 4.2-1 Demographic information of experts

Demographic factors		Frequency (Count)	Percentage
1. Gender	Male	5	100%
	Female	0	0%
2. Age group	26-40	3	60%
	41-65	2	40%
3. Education level	Diploma	1	20%

	Bachelors	2	40%
	Graduate	2	40%
4. Tunnelling Experience (Years)	1-5	1	20%
	6-10	2	40%
	Above 10	2	40%

4.2.2 Qualitative analysis and results

The initial analysis of tunnelling risk was achieved by means of a qualitative risk assessment. Qualitative risk analysis involves prioritizing the risks based on a pre-determined scale.

Frequency/likelihood response was a deductive analysis to estimate the frequency of the mentioned event based on experienced and/or expert judgments while *consequence* response was meant to identify all potential end consequence and also their probability of occurrence.

The response options were pre-defined as in Appendix 2-A as well as included in Questionnaire 1 under Questions 1 and 3. The combined risk likelihood and consequence responses from interviewing tunnelling experts are as in columns 3 and 4 of Table 4.3-2 below;

Based on the data collected through interviews and the pre-defined qualitative risk analysis scale in Appendix 2-B, qualitative risk analysis was conducted and the results are indicated in Table 4.2-2 below:

Table 4.2-2 Qualitative Risk Analysis results

Hazard Number	Hazard	Consequence	Risk Likelihood	Assessment
1	Accidents	Significant	Highly likely	Critical
2	Labour remonstration/ disputes	Major	Likely	Critical
3	Political change	Major	Somewhat likely	Serious
4	Defective work	Major	Likely	Critical

Hazard Number	Hazard	Consequence	Risk Likelihood	Assessment
5	Delay in material delivery	Major	Likely	Critical
6	Plant and machinery failure	Significant	Highly likely	Critical
7	Manual tasks	Moderate	Likely	Serious
8	Subsurface geological conditions	Moderate	Likely	Serious
9	Subsurface hydrogeological conditions	Moderate	Likely	Serious
10	Acts of God (earthquake, fire etc.)	Catastrophic	Somewhat likely	Critical
11	Delayed dispute resolution	Moderate	Likely	Serious
12	Change order negotiation	Significant	Occasional	Serious
13	Delayed payment on contract and extras	Significant	Occasional	Serious
14	Late drawings and instructions	Significant	Occasional	Serious
15	Delayed site access	Significant	Very unlikely	Important

Discussion of results

Based on the results of the qualitative risk analysis, it was noted that accidents, labour disputes, stop work orders on defective work, delay of material delivery, plant and machinery failure and acts of good were deemed *critical* to the delay in completion schedule. If the project is to be completed on schedule, those risks had to be mitigated by the parties concerned.

It should be noted that this type of analysis doesn't project the amount of delay for the project parties to decide whether the delay will be significant to significantly impact the project cost in comparison to the mitigation cost.

4.2.3 Severity Analysis ad Results

Based on a pre-defined scale in Appendix 3-A also included in the questionnaire under question 2 of Questionnaire 1, the respondents were required to attach a probability value to the qualitative responses they had indicated in the previous section under Question 1 of Questionnaire 1. Probability/likelihood was ranked on a scale of 0-100% probability of a risk occurring based on expert opinion. The responses obtained from experts 1, 2 and 3 (Contractor) and Experts 4 and 5 (Consultant) are as in Table 4.2-3 below.

It can be observed that the Contractor and Consultant have some biasness in the responses to the risks for which they are directly held accountable giving them a lower rating. For example, the responses from the Contractor's experts regarding Labour remonstration, defective work, delay in material delivery and manual tasks have a much lower probability compared to those allocated by the Consultant's respondents. Similarly, delayed dispute resolution, change order negotiation, delayed payment on contract and extras and late drawings and instructions have been grossly underscored by the Consultant.

The post interview analysis involved taking averages of the responses from the Contractor and the Consultant to overcome the biasness in responses. The results of this analysis are as in Table 4.2-4 below:

Table 4.2-3 Drill and Blast Tunnelling Schedule Risk Interview Results

Hazard Number	Hazard	Likelihood		Probability	
		Contractor	Consultant	Contractor	Consultant
1	Accidents	Highly likely	Highly likely	85%	95%
2	Labour remonstration/ disputes	Occasional	Highly Likely	40%	75%
3	Political change	Somewhat likely	Somewhat likely	15%	15%
4	Defective work	Occasional	Highly likely	45%	65%
5	Delay in material delivery	Occasional	Highly likely	50%	88%
6	Plant and machinery failure	Highly likely	Highly likely	85%	90%
7	Manual tasks	Occasional	Highly likely	30%	75%
8	Subsurface geological conditions	Likely	Likely	50%	50%
9	Subsurface hydrogeological conditions	Likely	Likely	50%	50%

Hazard Number	Hazard	Likelihood		Probability	
		Contractor	Consultant	Contractor	Consultant
10	Acts of God (earthquake, fire etc.)	Somewhat likely	Very unlikely	10%	1%
11	Delayed dispute resolution	Likely	Occasional	70%	40%
12	Change order negotiation	Likely	Somewhat likely	65%	15%
13	Delayed payment on contract and extras	Likely	Somewhat likely	60%	30%
14	Late drawings and instructions	Likely	Somewhat likely	60%	30%
15	Delayed site access	Somewhat likely	Very unlikely	2%	0%

Table 4.2-4 Outcome of interview data analysis

Hazard Number	Hazard	Combined Consequence	Combined Likelihood	Average Probability
1	Accidents	Significant	Highly likely	90%
2	Labour remonstration/ disputes	Major	Likely	58%
3	Political change	Major	Somewhat likely	15%
4	Stop work order/Defective work	Major	Likely	55%
5	Delay in material delivery	Major	Likely	69%
6	Plant and machinery failure	Significant	Highly likely	88%
7	Manual tasks	Moderate	Likely	53%
8	Subsurface geological conditions	Moderate	Likely	50%
9	Subsurface hydrogeological conditions	Moderate	Likely	50%
10	Acts of God (earthquake, fire etc.)	Catastrophic	Somewhat likely	6%
11	Delayed dispute resolution	Moderate	Likely	55%
12	Change order negotiation	Significant	Occasional	40%
13	Delayed payment on contract and extras	Significant	Occasional	45%
14	Late drawings and instructions	Significant	Occasional	45%
15	Delayed site access	Significant	Very unlikely	1%

The consequence rating was pre-defined as a 1-5 scale, with five being the highest consequence on project completion schedule while the Likelihood rating scale was from 1-6 with 6 as a rating for probability of occurrence exceeding 70% and 1 as a probability of risk occurrence less than

0.01%. The pre-defined Likelihood and Consequence ratings are in Appendix 3-A. Arising out of Table 4.2-4 by drawing inferences from Appendix 3-A, the outcome of the ratings for Consequence and Likelihood are as indicated in Column 3 and 4 of Table 4.2-4.

The hazard severity was determined using the formula in Equation 4.2-1 as:

$$\text{Severity} = \text{Likelihood Rating} * \text{Consequence Rating} \quad \ldots\ldots\ldots\ldots\ldots \textit{Equation 4.2-1}$$

Risk scores for all the events were determined by multiplying the severity of the event with the consequence rating and the results presented in Table 4.2-5 below.

Categorization of risks was based on inferences drawn from pre-defined table in Appendix 3-B and C.

Table 4.2-5 Severity risk assessment Matrix

Hazard Number	Hazard	Consequence Rating	Likelihood Rating	Severity = Likelihood X Consequence	Category
1	Accidents	3	6	18	Intolerable
2	Labour remonstration/ disputes	4	5	20	Intolerable
3	Political change	4	3	12	Critical
4	Defective work	4	5	20	Intolerable
5	Delay in material delivery	4	5	20	Intolerable
6	Plant and machinery failure	3	6	18	Intolerable
7	Manual tasks	2	5	10	Serious

Hazard Number	Hazard	Consequence Rating	Likelihood Rating	Severity = Likelihood X Consequence	Category
8	Subsurface geological conditions	2	5	10	Serious
9	Subsurface hydrogeological conditions	2	5	10	Serious
10	Acts of God (earthquake, fire etc.)	5	3	15	Critical
11	Delayed dispute resolution	2	5	10	Serious
12	Change order negotiation	3	4	12	Critical
13	Delayed payment on contract and extras	3	4	12	Critical
14	Late drawings and instructions	3	4	12	Critical
15	Delayed site access	3	2	6	Serious

Discussion of results

Based on results of the severity risk analysis, it was noted that accidents, labour disputes, defective work, delay of material delivery and plant and machinery failure were deemed intolerable hazards to the delay in completion schedule. If the project is to be completed on schedule, those risks must be eliminated or transferred since the risk may jeopardize the entire project, or its duration may be manifold that of the project. It should be noticed that the results of severity analysis for 'intolerable' risks almost compare with the 'critical' risks from qualitative risk analysis except for 'Acts of God'.

According to the predefined table in Appendix 3-B, based on the highly expected risk occurrence that are 'intolerable', the cycle duration will be extended by a duration of **3-5 days (Averagely 4 days)**

Therefore Maximum Cycle duration = 611 +4*8*60 = <u>2531minutes</u>

4.2.4 DEMATEL Correlation Analysis and Results

From the results of Severity analysis in Table 4.2-5, since the 'intolerable' risks are those that have a major influence on the completion schedule, they were selected for correlation analysis. This was aimed at determining how the occurrence of one risk may affect/lead to occurrence of another in the same tunnelling cycle. This analysis assumed that all the other risks do not significantly alter the completion schedule when they occur.

Under the Questionnaire 2, Question 2 was developed for applying DEMATEL method for the tunnelling experts to construct the causal relations among the criteria by indicating the direct influence each schedule risk has on another based on the 0-3 scale. Participants were asked the influence each schedule risk has on another on a scale of 0-3 where 0 = no influence, 1 = weak direct influence, 2 = moderate direct influence, and 3 = strong direct influence.

The direct influence matrices (X1, X2, X3, X4 and X5) from each tunnelling expert 1-5 are as in Appendix 4.

From Equation 3.5-1 and Appendix 4, the Average Direct Relationship Matrix Z was determined as in Table 4.2-6. This enabled elimination of biasness and reduction of the error in the responses.

Table 4.2-6 Average Influence Matrix, Z

	i	**1**	**2**	**3**	**4**	**5**
j	**Schedule Risks**	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
1	Accidents	0.0000	2.6000	1.6000	0.8000	1.6000
2	Labour remonstration	1.8000	0.0000	1.6000	2.0000	1.4000

	i	**1**	**2**	**3**	**4**	**5**
3	Defective work	2.0000	0.6000	0.0000	1.4000	1.0000
4	Delay in material delivery	2.4000	1.6000	1.8000	0.0000	1.4000
5	Plant and machinery failure	2.2000	1.4000	1.8000	2.2000	0.0000

Obtaining the sum of each row of Matrix Z gave values of $\sum Z_{ij}$ indicated in Table 4.2-7 below.

Table 4.2-7 Obtaining S from sum of each row

j	**Schedule Risks**	**Sum Zij**
1	Accidents	6.6
2	Labour remonstration	6.8
3	Defective work	5
4	Delay in material delivery	7.2
5	Plant and machinery failure	7.6

Based on Equation 3.5-2, **S = 7.6** (Maximum value of the sum of each row) to be used for normalization of the average influence matrix.

From Equation 3.5-3, the normalized direct-relation matrix ***D*** was obtained as in Table 4.2-8:

Table 4.2-8 Normalized direction Matrix, D

	i	**1**	**2**	**3**	**4**	**5**
j	**Schedule Risks**	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
1	Accidents	0.00000	0.34211	0.21053	0.10526	0.21053
2	Labour remonstration	0.23684	0.00000	0.21053	0.26316	0.18421
3	Defective work	0.26316	0.07895	0.00000	0.18421	0.13158
4	Delay in material delivery	0.31579	0.21053	0.23684	0.00000	0.18421
5	Plant and machinery failure	0.28947	0.18421	0.23684	0.28947	0.00000

Determining the Total-Relation matrix, T

From Equation 3.5-6 using Scilab software, the Total- Relation Matrix, T was determined as in Table 4.2-9;

Table 4.2-9 Total-Relation Matrix, T

	i	**1**	**2**	**3**	**4**	**5**
j	**Schedule Risks**	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
1	Accidents	1.41890	1.40840	1.37211	1.21771	1.17355
2	Labour remonstration	1.65590	1.18000	1.40778	1.35009	1.18413
3	Defective work	1.33367	0.99277	0.94728	1.02330	0.90838
4	Delay in material delivery	1.76587	1.40621	1.47544	1.18292	1.22706

	i	**1**	**2**	**3**	**4**	**5**
j	**Schedule Risks**	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
5	Plant and machinery failure	1.83226	1.45145	1.54480	1.47544	1.12817

Obtaining the sum of Columns and Rows

Determining Vectors **R** (sum of rows) and ***D*** (sum of columns) where R is a 5 x 1 and D is a 1 x 5 vectors respectively.

From equations 3.5-7 and 3.5-8, vector R_i and D_j were obtained as in Tables 4.2-10 and 4.2-11 respectively.

Table 4.2-10 Vector R_i

		Vector R*i*
1	Accidents	6.59066
2	Labour remonstration	6.77789
3	Defective work	5.20539
4	Delay in material delivery	7.05750
5	Plant and machinery failure	7.43212

Table 4.2-11 Vector Dj

	1	**2**	**3**	**4**	**5**
	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
Vector D*j*	8.006590	6.438837	6.747402	6.249452	5.621290

From Equation 3.5-10 the total effects given and received by each factor (for $i = j$) are as indicated in the Table 4.2-12 below. It can be observed that accidents have the most combined effects (given and received) compared to Delay in material delivery, Labour remonstration, Plant and machinery failure and Defective work respectively.

Table 4.2-12 Total effects received and given by a factor

Factor	**D*i* + R*i***
Accidents	14.59725
Labour remonstration	13.21672
Defective work	11.9528
Delay in material delivery	13.30695
Plant and machinery failure	13.05341

From equation 3.5-11, for $i = j$ as indicated in the Table 4.2-13 below, it can be seen that accidents and defective work are net causes (+ve difference) while Labour remonstration, delay in material delivery and plant and material failure are net receivers (-ve difference).

Table 4.2-13 Determining if a factor is a net cause (+) or net receiver (-)

Factor	D*i* - R*i*
Accidents	1.415927
Labour remonstration	-0.3390511
Defective work	1.5420079
Delay in material delivery	-0.8080496
Plant and machinery failure	-1.8108342

As per the results in Table 4.2-12, it is indicated that risk factors accidents and defective work are net givers while labour remonstration, delay in material delivery and plant and machine failure are net receivers.

Setting the Threshold Value, α

The threshold value, α was determined as an average of elements in Matrix T from Equation 3.5-12. Any value less than the threshold in the total influence matrix was considered non influential and was to be eliminated.

Therefore α = **1.3225**

Constructing the Impact Relationship Map (IRM)

After comparing the elements of matrix T with the value of α, the elements of T whose values are less than α are assigned a value of zero, to yield a new matrix called α-cut total influence matrix Tα in Table 4.2-14.

Table 4.2-14 α-cut Total Influence Matrix, Tα

	i	**1**	**2**	**3**	**4**	**5**
j	**Schedule Risks**	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
1	Accidents	1.41890	1.40840	1.37211	0.00000	0.00000
2	Labour remonstration	1.65590	0.00000	1.40778	1.35009	0.00000
3	Defective work	1.33367	0.00000	0.00000	0.00000	0.00000
4	Delay in material delivery	1.76587	1.40621	1.47544	0.00000	0.00000
5	Plant and machinery failure	1.83226	1.45145	1.54480	1.47544	0.00000

Discussion of results

The values obtained under the α-cut Total Influence Matrix in Table 4.2-14 indicate how the risk occurrences under Column *j* are related/effect the risks under Row *i*.. For instance, it is inferred that when considering Accidents risk occurrence, delay in material delivery and plant and machinery failure have no influence at all while accidents, labour remonstration and defective work have their influence weighted as 1.41890, 1.40840 and 1.37211 respectively. These correlations are used as weights for the respective risk inputs in the subsequent simulation analysis using Monte Carlo and Discrete Event Simulation using ARENA.

4.2.5 Monte Carlo Simulation Analysis and results

From Question 1 of the Questionnaire 2, for a tunnelling cycle, based on expert opinion, estimates of the mean duration, the absolute maximum duration, in the worst possible case, and the absolute minimum duration, in the best possible case it would take to complete each activity in the cycle were made. The most likely activity duration was as per the CPM schedule. The results are as indicated in the Table 4.2-15 below:

Table 4.2-15 Estimates of cycle activity durations

I/No.		ACTIVITY	CYCLE TIME (Minutes)		
			MIN	MOST LIKELY	MAXIMUM
1	EXCAVATION	DRILLING			
1.1		Placing Jumbo	19	23	27
1.2		Drilling	130	143	155
1.3		Displace Jumbo	15	18	20
2		CHARGING			
2.1		Load Explosives	43	57	69
3		BLASTING			
3.1		Blasting	24	27	30
4		VENTILATION			
4.1		Ventilation	15	19	24

I/No.		ACTIVITY	CYCLE TIME (Minutes)		
			MIN	MOST LIKELY	MAXIMUM
5	MATERIAL HANDLING	MUCKING			
5.1		Maneuver truck	10	14	19
5.2		Load soil	40	55	65
5.3		Transfer soil	25	33	40
5.4		Unload soil	18	27	35
6		SCALING			
6.1		Mechanical scaling	25	30	35
6.2		Manual scaling	40	47	55
7		**SHOTCRETE**			
7.1		Shotcrete	15	23	30
8	PRIMARY SUPPORT	PRIMARY SUPPORT AND LINING			
8.1		Transfer Lining	7	10	14
8.2		Unload Lining	13	19	25
8.3		Ground support & Final lining	35	45	54
9	MINOR PROCE	SURVEYING, SETTING UP etc			

I/No.		ACTIVITY	CYCLE TIME (Minutes)		
			MIN	MOST LIKELY	MAXIMUM
9.1		Surveying and set up	13	21	30
TOTAL CYCLE TIME			**487**	**611**	**727**

Gross tunnelling cycle time distribution is as indicated in Figure 4.2-1 below:

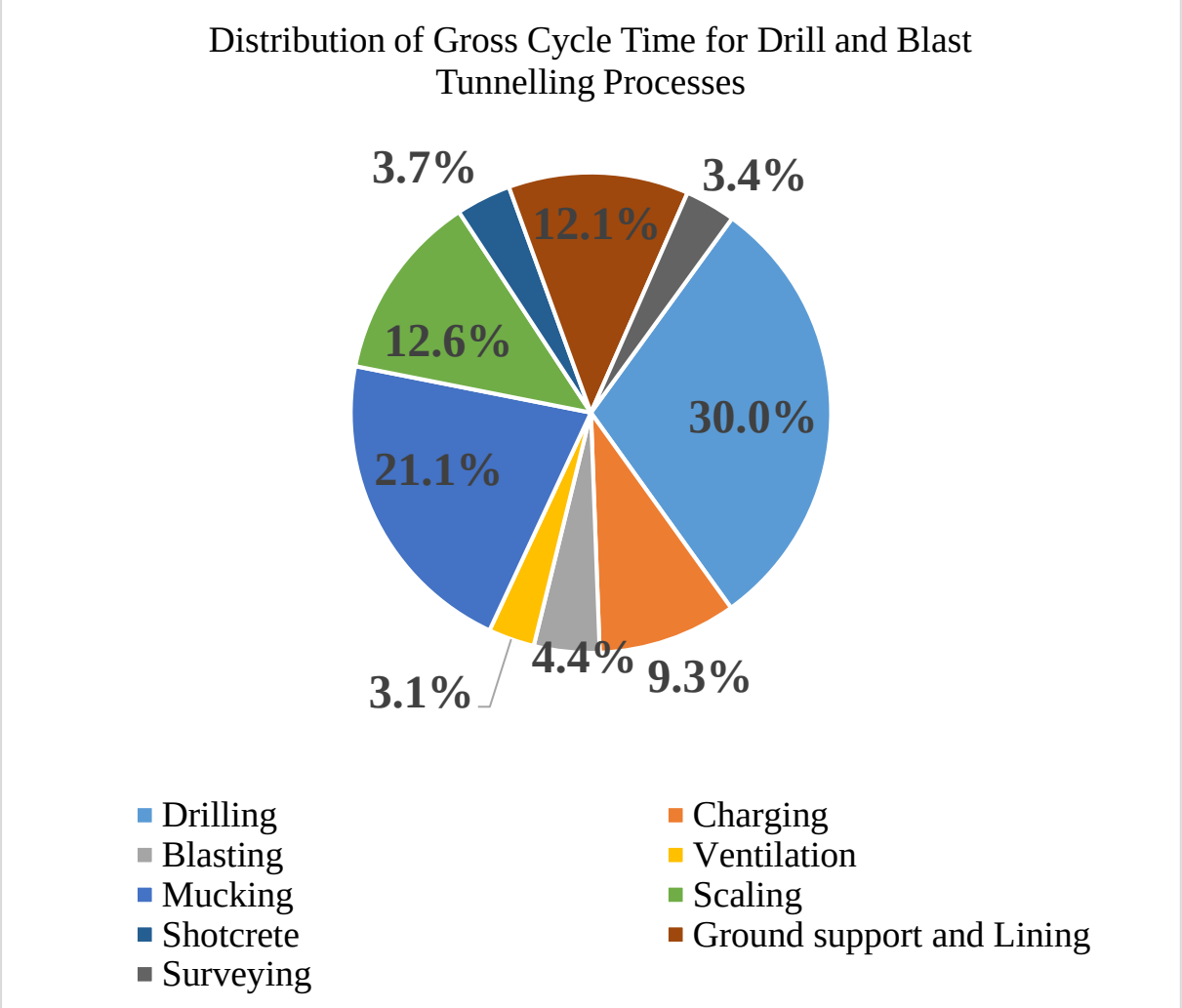


Figure 4.2-1 Gross tunnelling cycle time distribution

Selection of Probability Distribution

According to the expert opinions for this study the triangular distribution was deemed most suitable distribution. The rationale for this their opinion was that there is a higher probability of occurrence of the values around the most likely value, which are the values of the time durations of the activities estimated for research and were decided upon in the planning phase. In addition, no historical data had by the time of the interview been analyzed to provide the best curve fit.

Using MCS computer model, a range of possible outcomes were simulated, and presented along with their probabilities of occurrence. In the simulation, a spreadsheet was used to calculate some desired result (in our case, the total tunnelling cycle critical-path duration) using @Risk excel Add-in. In a MCS, the computer varied each input within a predetermined range hundreds of times and generated a range of outputs along with the frequency of these outputs' occurrence. This frequency translated into the probability of the respective output's occurrence. With MCS, instead of a single estimated date, we generated a mathematical distribution showing the likely range of outcomes. Using this method, if a project manager needs the project to be completed by a certain date, we can quantify the probability of meeting this date. This demonstrates the risk in the model. Based on this information, we might make different choices when planning the project.

Incorporating risk

By building a risk register in excel, @RISK was used for defining distributions which calculated whether or not a risk would occur and the size of its impact on schedule. Only those risks that were defined as 'intolerable" from severity analysis were included in the risk register.

The risks in a register come into "action" during a simulation. Each iteration, @RISK sampled whether or not a specific risk occurred. The size of risk impacts were sampled too. The impacts of risks in the register were linked via Excel formulas to the tasks in the project.

Performance of deterministic computations

For modeling in @Risk, a formula in a cell that references an impact value in the Register was used. For example, on the Tasks sheet, the formula for **Drilling** duration in cell B5, *=RiskTriang(130,143,155)+'Risk Register'!L5.* During a simulation, this formula calculates the duration of the Drilling task by summing two values. First, an @RISK distribution - RiskTriang(130,143,155) – generates a base duration between 130 and 155 days. The

respective 3 point estimates for each activity are as in Table 4.3-5 above. Then, the impact of the **Machine Breakdown Risk** from the Register (in terms of additional minutes required to Drilling from cell 'Risk Register'!L5) is added, if this risk occurs.

Due to the correlations between risks as seen from Table 4.2-14 (DEMATEL analysis results), occurrence of one risks may indirectly lead to occurrence of other risks. Each of these risks has particular tasks whose schedule it directly impacts as in Table 4.2-16 below:

Table 4.2-16 Risks and the tasks whose schedules are directly impacted

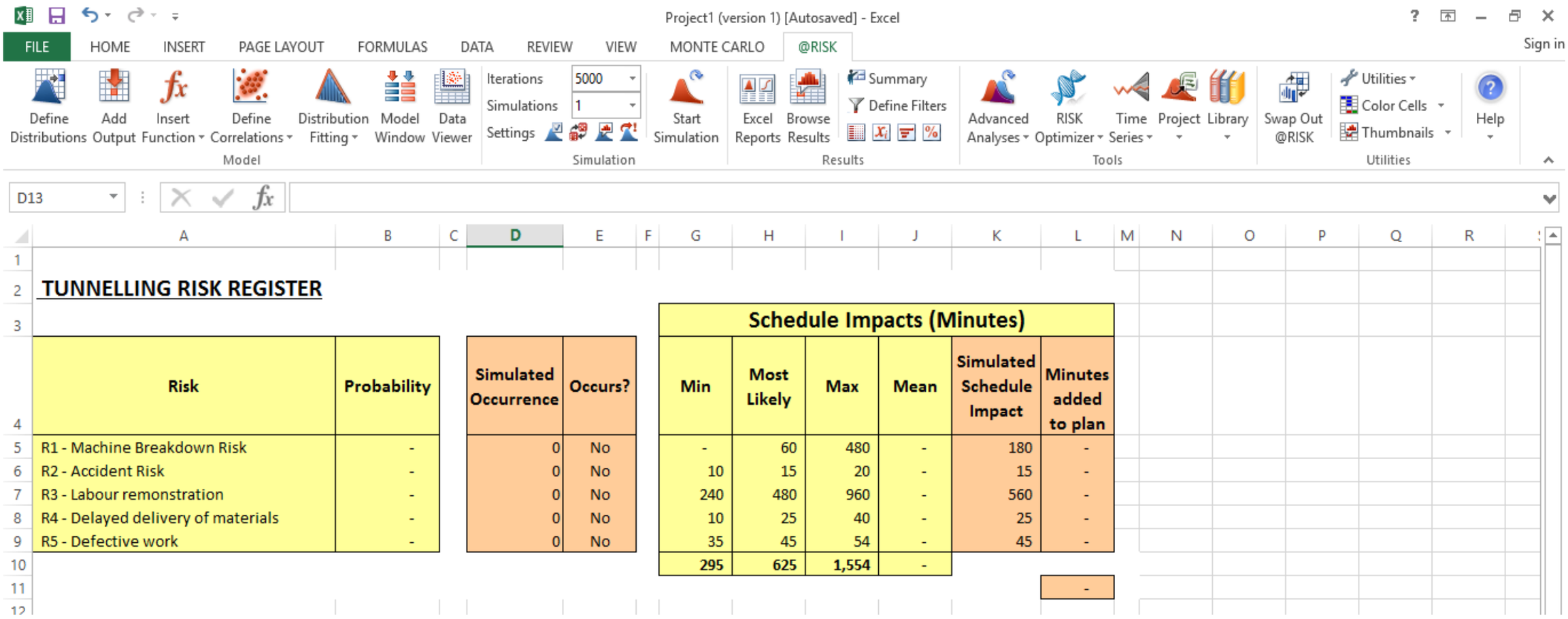
#	Risk	Schedule Impacted tasks
1	R1 - Machine Breakdown Risk	Drilling and Shotcrete
2	R2 - Accident Risk	Ventilation (normally occur after blasting from falling rocks)
3	R3 - Labour remonstration	Ventilation (majorly initiated by accident occurrence)
4	R4 - Delayed delivery of materials	Shotcrete and Transfer Lining and Ground support material
5	R5 - Defective work	Final Lining and Ground Support

The Risk Register applied in @RISK simulation is as seen in Table 4.4-13 below.

Number of iterations

For better results and to avoid taking so much time, 5,000 iterations were considered sufficient for this simulation.

Table 4.2-17 Tunnelling Risk Register



TUNNELLING RISK REGISTER

					Schedule Impacts (Minutes)					
	Risk	Probability	Simulated Occurrence	Occurs?	Min	Most Likely	Max	Mean	Simulated Schedule Impact	Minutes added to plan
5	R1 - Machine Breakdown Risk	-	0	No	-	60	480	-	180	-
6	R2 - Accident Risk	-	0	No	10	15	20	-	15	-
7	R3 - Labour remonstration	-	0	No	240	480	960	-	560	-
8	R4 - Delayed delivery of materials	-	0	No	10	25	40	-	25	-
9	R5 - Defective work	-	0	No	35	45	54	-	45	-
10					**295**	**625**	**1,554**	-		
11										-

Simulation Formulae

1. Simulated Occurrence (for Cell D5) =*RiskDiscrete({1,0},B5:C5,RiskStatic(0))*
2. Occurs? (Cell E5) =*IF(D5>0,"Yes","No")*
3. Simulated Schedule Impact (Cell K5) =*RiskTriang(G5,H5,I5)*
4. Minutes added to Plan (Cell L5) =RiskMakeInput(K5*D5,RiskName(A5&" Schedule Impact"))

Note: The rest of the respective cells followed the same formulae.

Simulation results

From the @RISK distributions, the generated base durations for each activity in the tunnelling cycle are as indicated in Table 4.2-18

Table 4.2-18 @Risk generated base task durations

Name	Duration (min)	Start_Date	Finish_Date
Start Cycle	0	May 15, 2019 8:00 AM	May 15, 2019 8:00 AM
Cycle duration	**608**	**May 15, 2019 8:00 AM**	**May 16, 2019 10:11 AM**
Placing Jumbo	23	May 15, 2019 8:00 AM	May 15, 2019 8:23 AM
Drilling	143	May 15, 2019 8:23 AM	May 15, 2019 10:46 AM
Displace Jumbo	18	May 15, 2019 10:46 AM	May 15, 2019 11:04 AM
Load Explosives	56	May 15, 2019 11:04 AM	May 15, 2019 1:01 PM
Blasting	27	May 15, 2019 1:01 PM	May 15, 2019 1:28 PM
Ventilation	19	May 15, 2019 1:28 PM	May 15, 2019 1:47 PM
Maneuver truck	14	May 15, 2019 1:47 PM	May 15, 2019 2:01 PM
Load soil	53	May 15, 2019 2:01 PM	May 15, 2019 2:56 PM
Transfer soil	33	May 15, 2019 2:56 PM	May 15, 2019 3:29 PM
Unload soil	27	May 15, 2019 3:29 PM	May 15, 2019 3:56 PM
Mechanical scaling	30	May 15, 2019 3:56 PM	May 15, 2019 4:26 PM
Manual scaling	47	May 15, 2019 4:26 PM	May 16, 2019 8:13 AM
Shotcrete	23	May 16, 2019 8:13 AM	May 16, 2019 8:36 AM
Transfer Lining and ground support material	10	May 16, 2019 8:36 AM	May 16, 2019 8:46 AM
Unload Lining and ground support material	19	May 16, 2019 8:46 AM	May 16, 2019 9:05 AM

Name	Duration (min)	Start_Date	Finish_Date
Final Lining and ground support	45	May 16, 2019 9:05 AM	May 16, 2019 9:50 AM
Surveying and setting up	21	May 16, 2019 9:50 AM	May 16, 2019 10:11 AM
Cycle closeout	0	May 16, 2019 10:11 AM	May 16, 2019 10:11 AM

The generated excel 'Outputs results summary' report for each combination of risks gave the **minimum, mean and maximum 'minutes to be added to plan'** as seen in Appendix 5-D

MCS validation and verification

Validation and verification was conducted to ensure that the represented reality and worked as intended. This was conducted using parameter variability (Sensitivity Analysis) method. This technique consisted of changing the values of the risk input parameters of the model to determine the effect of output on the model's behavior. The same relations should occur in the model as in the real system. Risk parameters that were considered sensitive (i.e., cause significant changes in the model's behavior or output) were made sufficiently accurate prior to using the model by applying the correlations obtained from DEMATEL Analysis.

In Figure 4.2-2, the relationship between the probability of occurrence of accidents and the duration to be added to plan is shown. There is almost no significant increment in minimum, average and maximum duration to be added to plan with increasing probability of accident occurrence. The relationships are more or less constant. Accidents occurrence leads to occurrence of other correlated risks in form of labour remonstration as a result of safety concerns and defective work arising from discontinuities in working patterns.

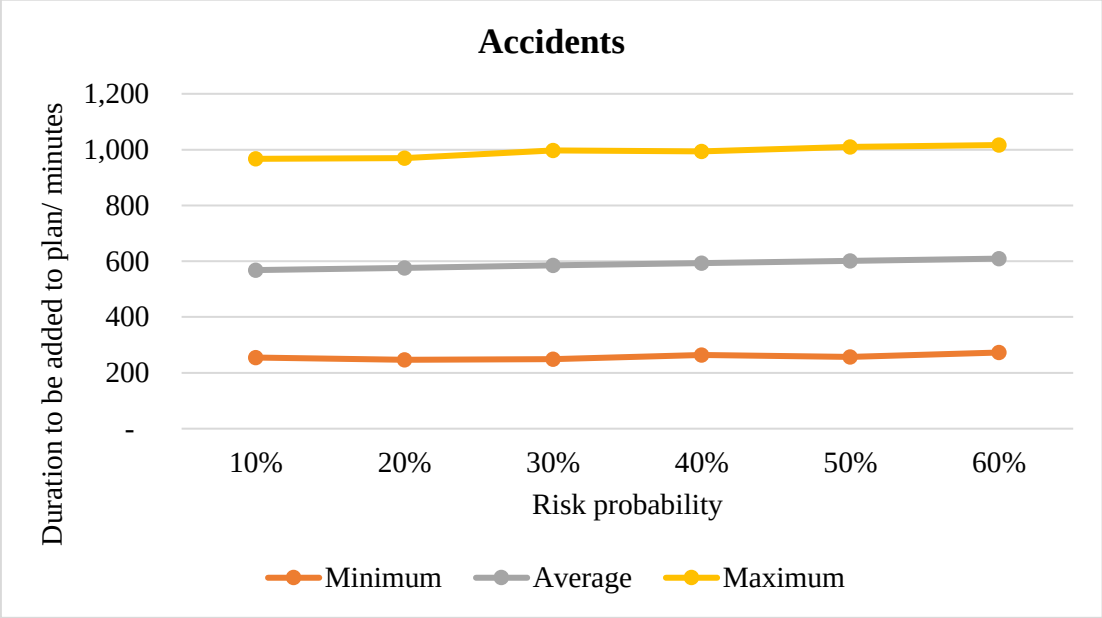


Figure 4.2-2 Sensitivity analysis on accident risk

In Figure 4.2-3, the relationship between the probability of occurrence of labour remonstration and the duration to be added to plan is shown. There is almost no significant increment in minimum and maximum duration to be added to plan by increasing the probability of labour remonstration occurrence. It is also noticed that the average duration to be added to plan increases significantly with increase in probability of occurrence of labour remonstration. Occurrence of labour remonstration increases the amount of time required to attend to labour remonstration consequences. Labour remonstration occurrence also leads to occurrence of other correlated risks in form of accidents especially if the remonstration becomes violent, delay in material delivery due to unavailable machine operators and defective work arising from discontinuities in working patterns. All these activities require extra time to effect the requisite remedies.

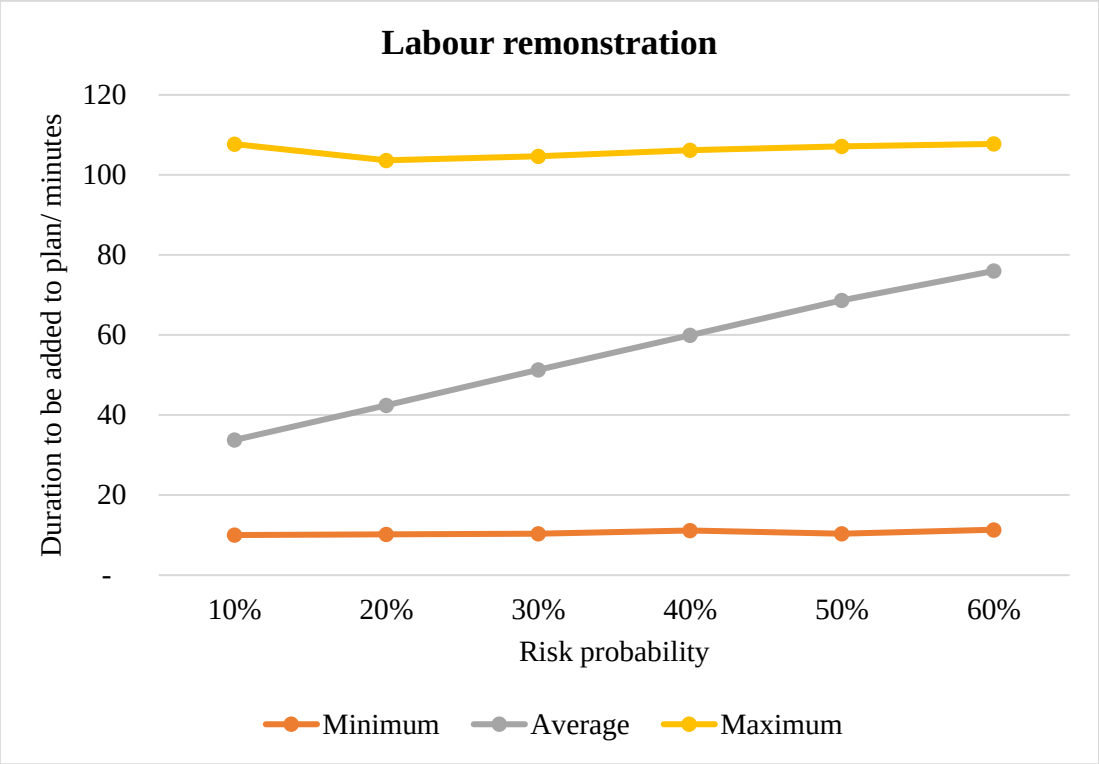


Figure 4.2-3 Sensitivity analysis on labour remonstration risk

In Figure 4.2-4 the relationship between the probability of occurrence of defective work and the duration to be added to plan is shown. There is almost no significant increment in minimum and maximum duration to be added to plan by increasing the probability of occurrence of defective work. It is also noticed that there is a perfectly linear relationship between probability of occurrence of defective work and the average duration to be added to plan. Occurrence of defective work increases the amount of time required to rectify the defective work which interventions may range from simple remedial work and other times include total demolition and reconstruction. Defective work occurrence also leads to occurrence of other correlated risks in form of accidents especially where the defective work is a safety risk as well. All these activities require extra time to effect the requisite remedies.

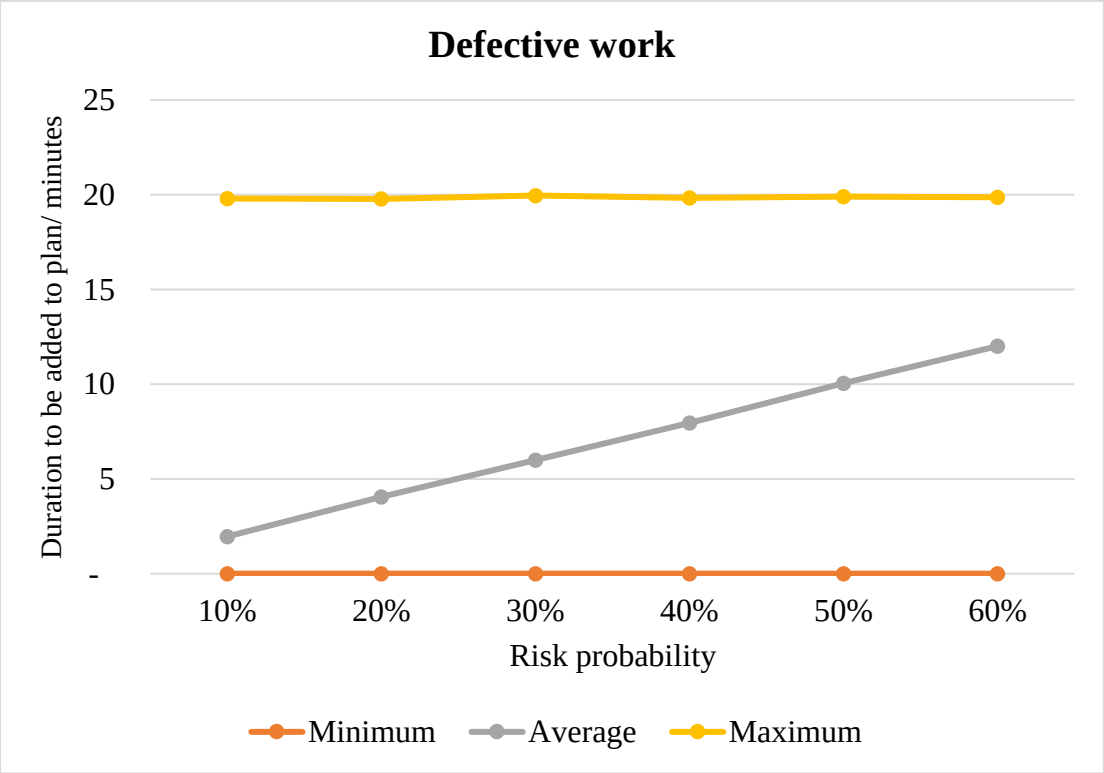


Figure 4.2-4 Sensitivity analysis on defective work risk

In Figure 4.2-5, the relationship between the probability of occurrence of delay in material delivery and the duration to be added to plan is shown. There is almost no significant increment in minimum, average and maximum duration to be added to plan with increasing probability of occurrence of delay in material delivery. Occurrence of delay in material delivery increases the amount of time required to conduct activities such as shotcreting, ground support and final lining due to the waiting time incurred. Delay in material delivery occurrence also leads to occurrence of other correlated risks in form of accidents especially where the contractors tries to speed up activities to recover lost time and also where the tunnel standup time is exceeded leading to eventual tunnel collapse. Excessive delay in material delivery may force the contractor to reduce pay days for casual labour in order to reduce costs which would ultimately result in labor remonstrations. The delay in material delivery may also result in defective work arising from discontinuities in construction cycles. All these activities require extra time to effect the requisite remedies.

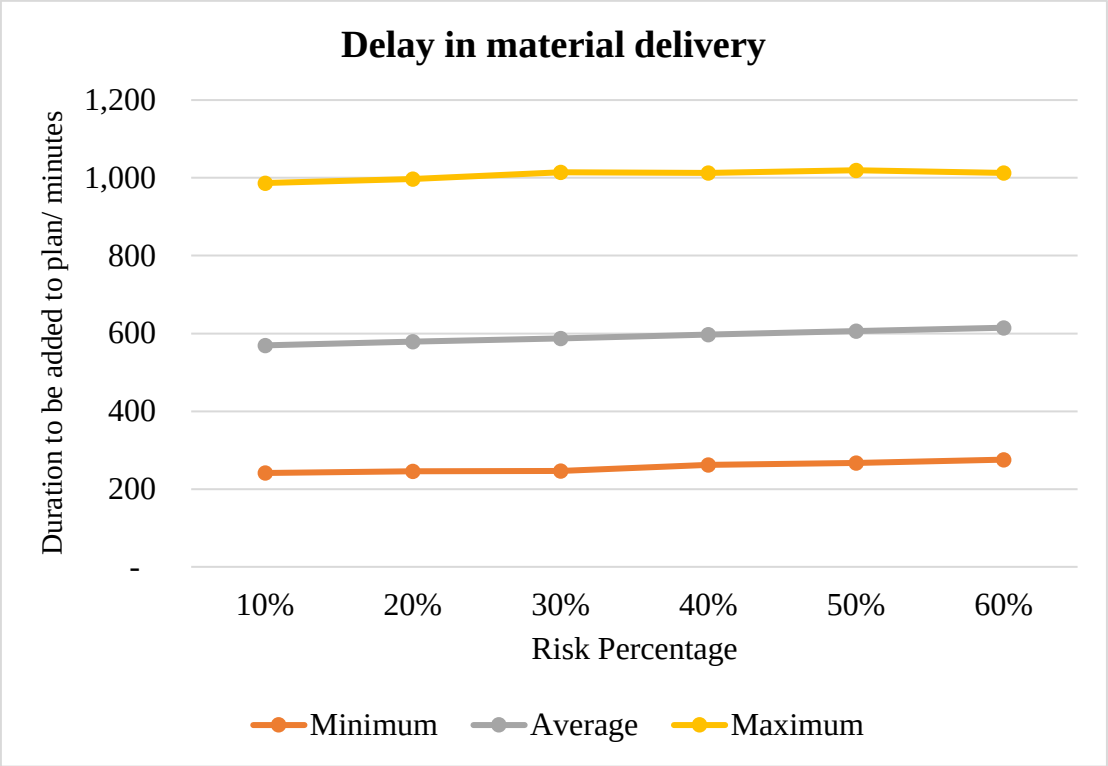


Figure 4.2-5 Sensitivity analysis on delay in material delivery risk

In Figure 4.2-6, the relationship between the probability of occurrence of plant and machine failures and the duration to be added to plan is shown. There is almost no significant increment in minimum, average and maximum duration to be added to plan with increase in the probability of occurrence of plant and machine failures. Occurrence of plant and machine failures increases the amount of time required to conduct activities such as drilling, shotcreting and rock bolting due to the repair time required. Delay due to plant and machine failures occurrence also leads to occurrence of other correlated risks in form of accidents especially where the contractors tries to speed up activities to recover lost time and also where the tunnel standup time is exceeded leading to eventual tunnel collapse. Excessive waiting due to plant and machine failures may force the contractor to reduce pay days for casual labour in order to reduce costs which would ultimately result in labor remonstrations. The plant and machine failures may also result in defective work arising from discontinuities in construction cycles. All these activities require extra time to effect the requisite remedies.

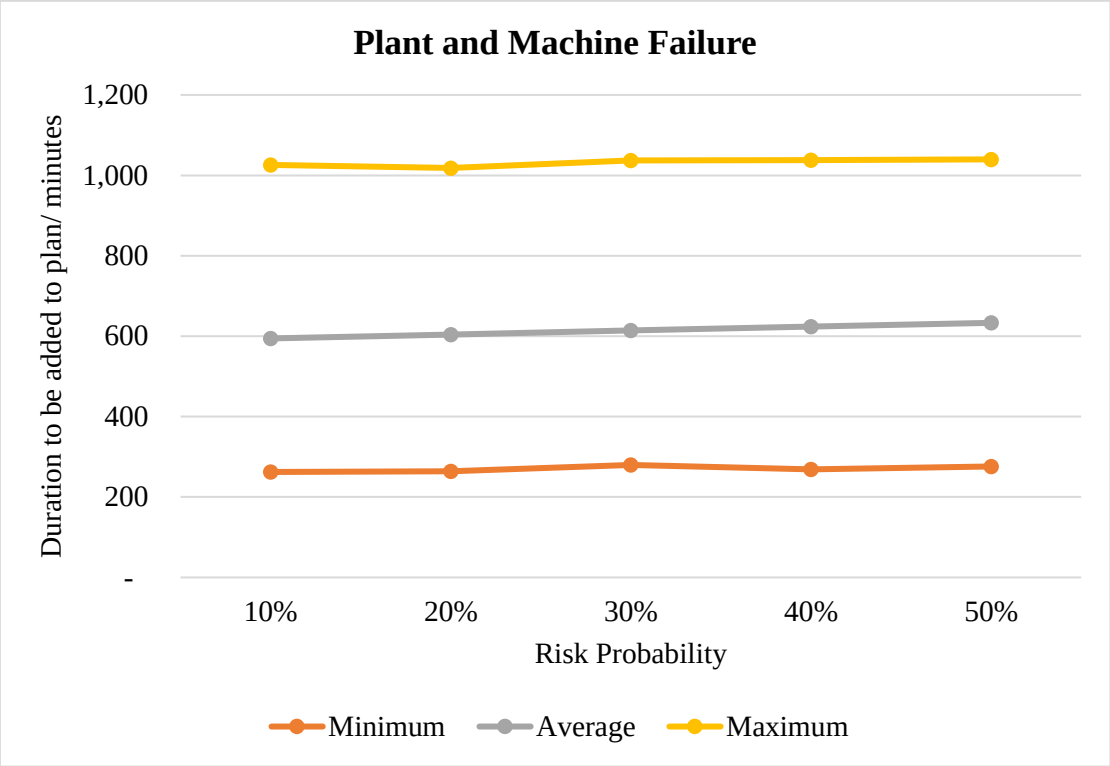


Figure 4.2-6 Sensitivity analysis on plant and machinery failure risk

Experimental design

Identification of significant factors

By performing the sensitivity analysis the effect of each individual risk variable on the duration added to plan is shown. Also the impact on the duration added to plan of the risk variables compared to each other may be assessed.

Sensitivity analysis carried out using Monte Carlo Simulation of the Awash-Kombolcha tunnels has shown the effect of tunnelling risks occurrence on the duration to be added to plan of the project. For tunnel excavated by drill and blast the analysis has shown that the risk variables ‘accidents’, ‘plant failure’ and ‘delayed material delivery’ have the biggest impact on the minimum, average and maximum tunnelling duration. The sensitivity analysis has also shown that the variables ‘labour remonstration’ and ‘defective work’ are less significant. Figure 4.2-7, 8 and 9 below show the results of the sensitivity analysis related to the Awash-Kombolcha tunnels excavated by conventional drill and blast.

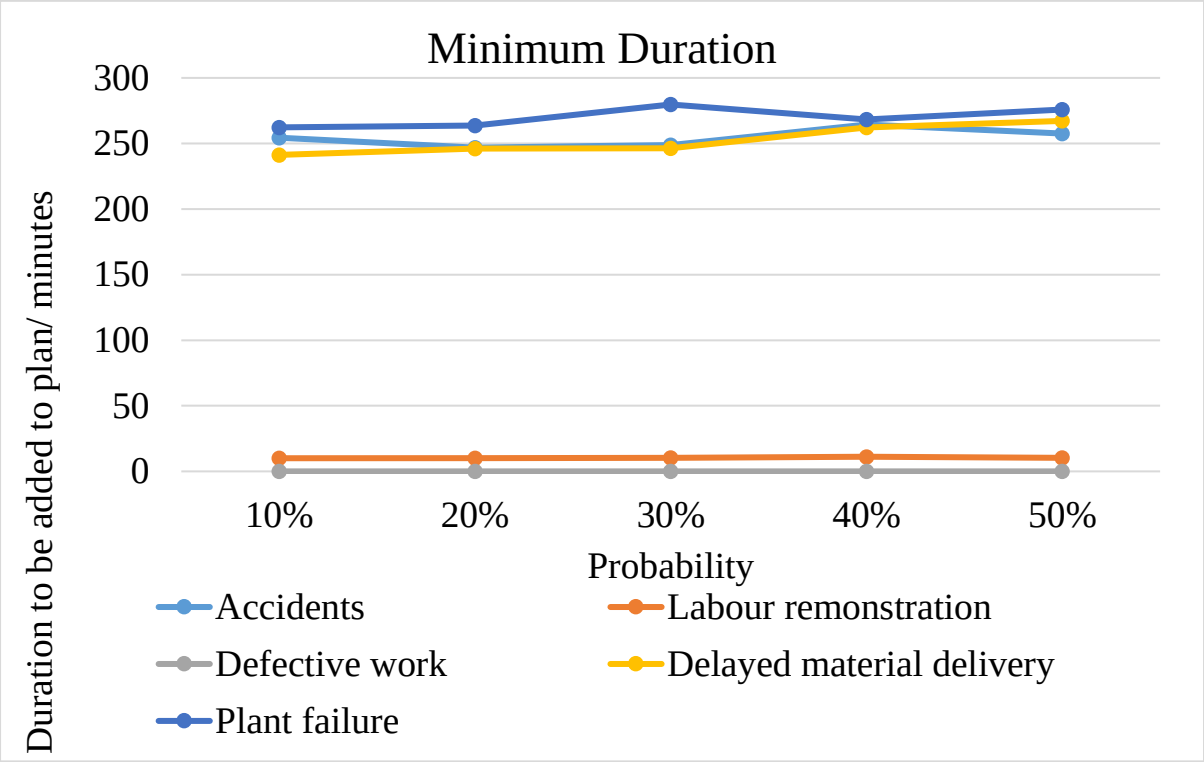


Figure 4.2-7 Sensitivity analysis results for minimum durations added to plan

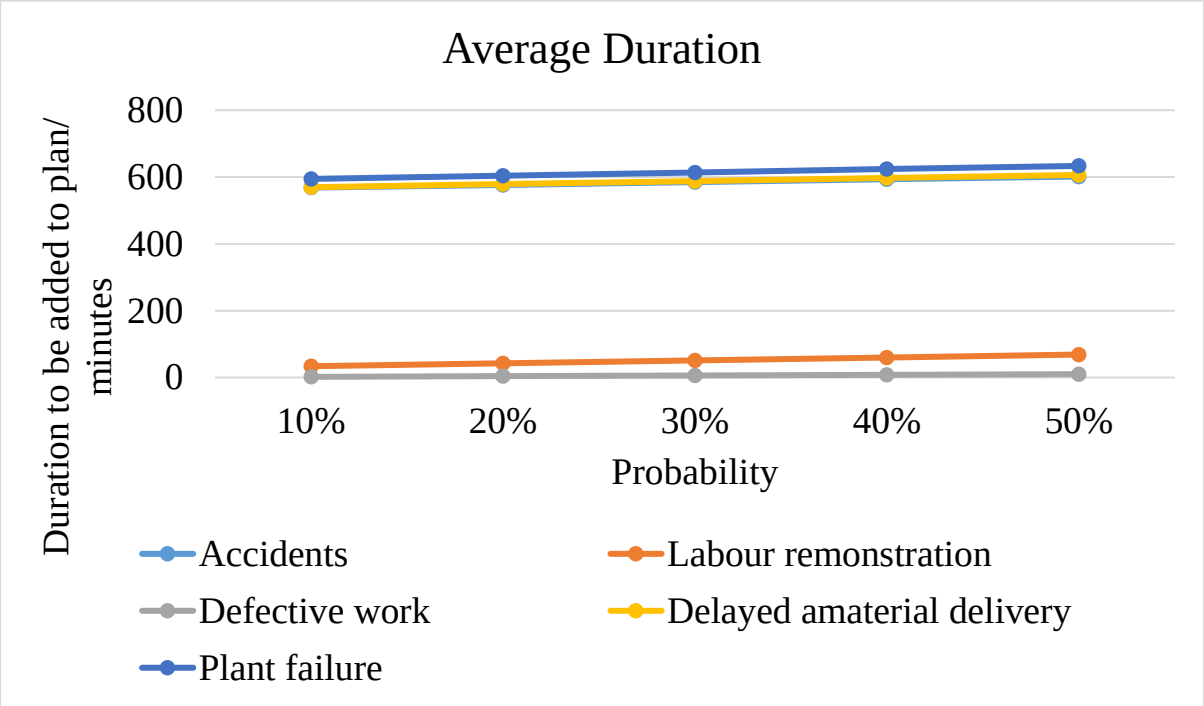


Figure 4.2-8 Sensitivity analysis results for average duration to be added to plan

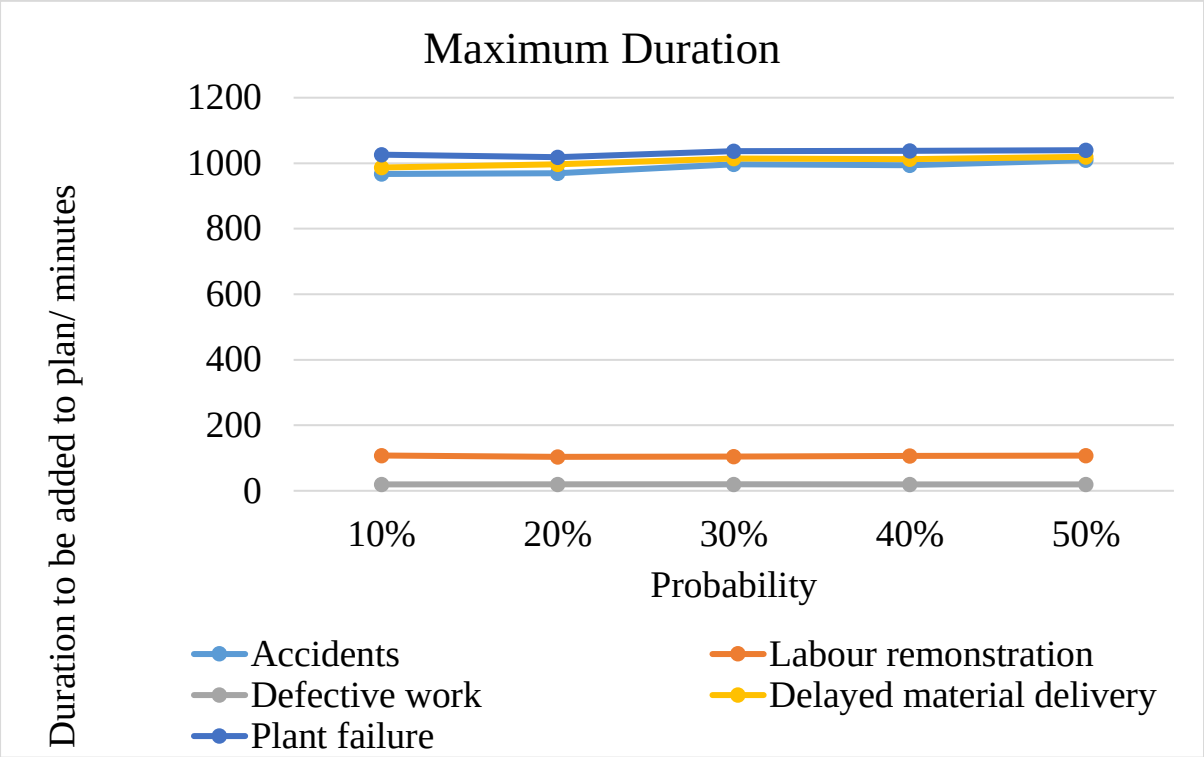


Figure 4.2-9 Sensitivity analysis results for maximum duration to be added to plan

From Figure 4.2-9, it is seen that the significant factors closely converge to give a maximum duration to be added to plan per cycle at a probability of occurrence of 30%. The Maximum duration to be added to cycle planned duration **as per MCS is estimated to be 1036.88 minutes.**

Therefore the MC simulated cycle duration = 608 + 1036.88 = **1644.88minutes**

4.2.6 Discrete Event Simulation

Introduction

As described in Section 3.5.5, in this section, an explanation to the risks related to Awash-Kombolcha drill and blast tunnelling sub-project (component), practice and problems, model development, data collection and input data analysis, identifying proper input parameters, developing and running simulation model using ARENA software, collecting output data from simulation acquired with subsequent analysis with different scenario and finally establishing the key research findings are discussed.

Awash-Kombolcha (AK) drill and blast tunnelling operation and Modeling the Operation

Awash-Kombolcha drill and blast tunnelling operation

To model the AK drill and blast tunnelling operation, it requires to study and investigate in detail the component, practice and problems of AK drill and blast tunnelling operation from the sample project. Accordingly, the AK drill and blast tunnelling operation or cycle has been studied through observation supported by document review. The observed AK drill and blast tunnelling operation is classified in to a repeated similar cycles with each having the following nine (9) processes; drilling, charging, blasting, ventilating, mucking, scaling, shotcreting, initial lining and ground support, and surveying. Those processes are characterized by a finish to start relationship. The process map is as seen in Figure 4.2-10

The studied site has faced different kind of schedule delay in AK drill and blast tunnelling processes. From the interviews, the major risks that have resulted in schedule delay include the following:

- Plant and Machinery breakdown especially the drilling jumbo
- Accident occurrences mainly due to falling rocks left loose with short stand-up time after drilling
- Labour remonstrations/strikes by works arising out of demand for more payment or safety issues
- Delayed delivery of materials especially for shotcreting, initial lining and primary support
- Defective work (cracking or major deformations) arising out of different occurrences which lead to repeated work especially in the initial lining and primary support.

Designing model in sequence and logical manner

Designing a drill and blast tunnelling cycle operation model in work sequence and logical manner starts with the identification of the problem and abstracting the overall operation process that occurred in the real-world. When the model is created, one should be able to describe the general workflow of the real construction process by simply following the journey of the entity within the model. As shown in Figure 4.2-10.

As shown in Figure 4.2-10, some major processes are characterized by uncertainties represented as decision points in the cycle. Modeling and simulating the logical sequence, the dynamics, and uncertainty of such operations needs the following:

First it requires the understanding and abstracting of the important processes, then representing those elements with equivalent symbols that are familiar with the simulation software language using a computer.

In addition, the development of simulation model requires a description of input and output parameters. The input requirement parameters are those to be collected from project site while the simulation experiment result output is that collected from simulation. The complete descriptions are listed in Table 4.2-19.

Table 4.2-19 Description of input and output parameters

No.	Parameter	Description
1	Input data	• Major resources for each process • Three point estimates of duration from Monte Carlo Simulation • Schedule risks, their probabilities of occurrence and correlations • Three point estimates of the duration of remedial actions following risk occurrence
2	Output data	• The minimum, average and maximum amount of time it takes for completion of an entire drill and blast tunnelling cycle

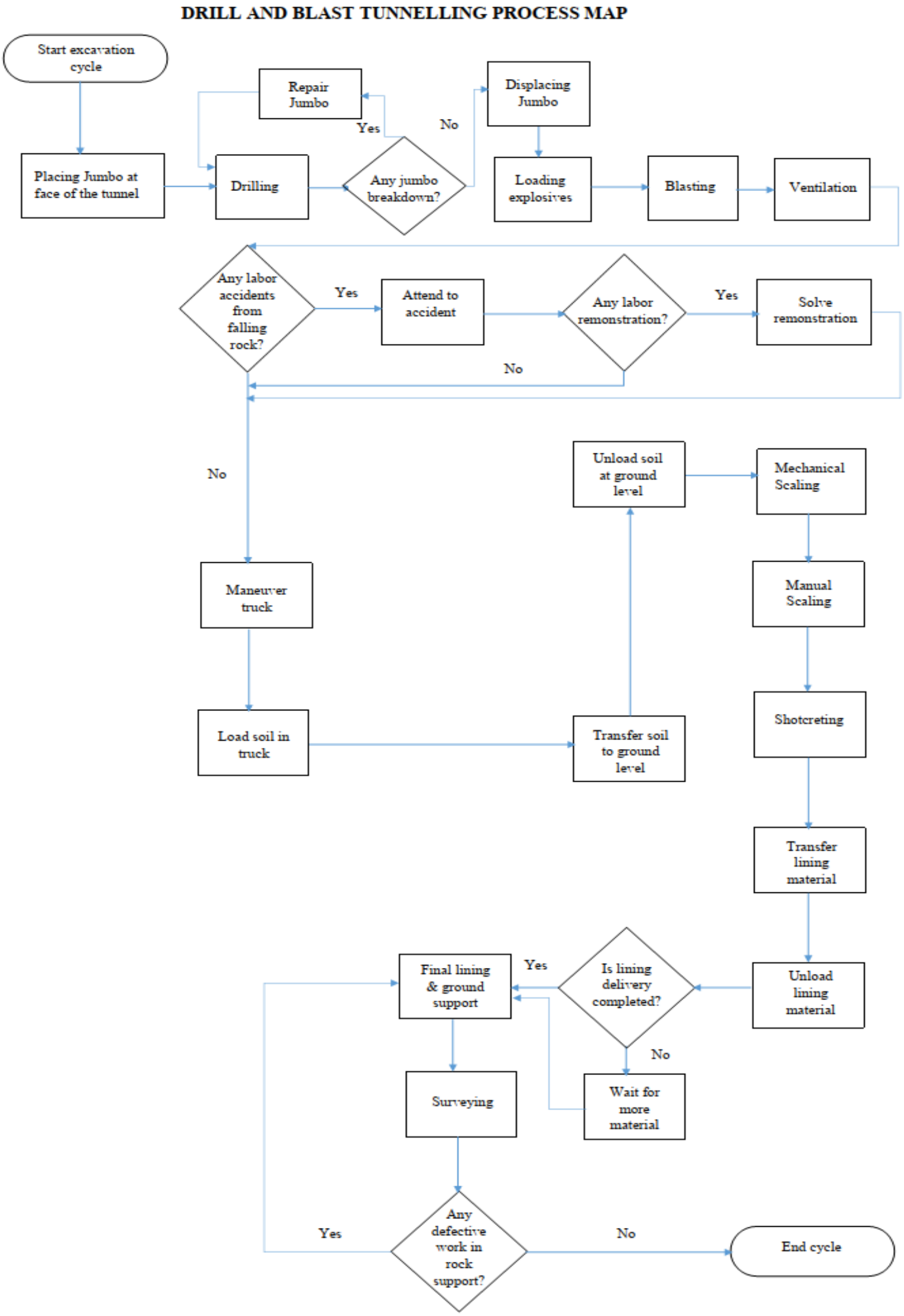


Figure 4.2-10 Drill and Blast process map

The pictorial model of drill and blast tunnelling operation which is developed in the process map in Figure 4.2-10 has to be simulated with suitable software. The modeling task typically involves abstraction and implementation of parts and the entire cycle on a computer. The suitable software which is selected to model the process of drill and blast tunnelling operation is ARENA v15.1 because of the following reasons:

- ARENA has a powerful graphical interface
- It consists of template modules that are constructed around SIMAN language
- The software is good for predicting system performance based on key metrics such as costs, throughput, cycle times, and utilizations
- Its student version is freely available and not limited by validity of the software except in model size.

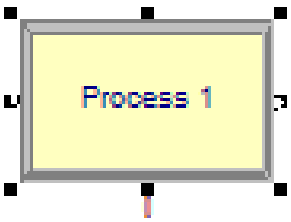
Using ARENA software, the model was developed as below:

The Entities in this case were the tunnelling cycles, and the processes were the tunnelling activities. The risks under study were included as Decision modules. The model was developed using the ARENA Basic simulation modules defined as below:

1 

Create Module:

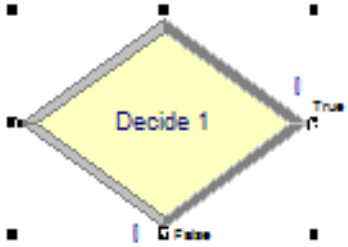
This module was used to define the entity to be created. In this case, the tunnelling cycle. The Create module was the starting point for an entity's flow through the system being modeled. Entities were created based on a time between arrivals. Entities would then leave the module to begin processing through the system.

2 

Process Module:

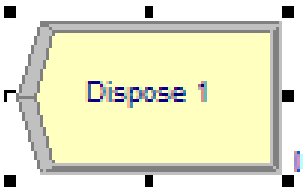
This module was used as the main processing method in the simulation. Since the processes have a finish to start relationship, the process action was considered to be a 'seize, delay, release' of the resources. The process time was allocated to the entity and considered to be value added and the

delay type taken as triangular due to time distribution of our data.

3 

Decide Module:

This module allowed for decision-making processes in the system. It included options to make decisions based risk occurrences (e.g., if entity type is based on one or more probabilities of risk occurrence (e.g., 75% true; 25% false).

4 

Dispose Module:

This module was used as the ending point for entities in a simulation model.

Overall drill and blast tunnelling operation model developed by using ARENA simulation software is as indicated in the Figures 4.2-11 to 4.2-13 below.

Designing and building a simulation model goes beyond describing and representing the entire operation process in graphical and abstracted symbols. It also involves properly collecting and modeling input data to the model for every single cycle, with clearly defined parameters. The development of model input data and their parameters are describing those important risk factors that affect schedule for the AK drill and blast tunnelling operation. Generally, this can be classified into two important categories which are process oriented and performance oriented, the discussion of this section is based on observation of real operation

A. AK drill and blast tunnelling process oriented

AK drill and blast tunnelling process oriented: refers to the factors affecting the drill and blast tunnelling process by identifying how much time is required to execute specific processes within a tunnelling cycle. E.g. (Duration of drilling, charging, blasting, ventilating, mucking, scaling etc.).

These activities and their three point durations have already been identified under section Table 4.2-15 (Monte Carlo Simulation). The results 3–point durations from MCS for each process will be utilized as inputs in this section.

However, when uncertainities occur, the 'standard' tunnelling processes are extending by including extra processes intended to rectify the effects of the uncertainity/risk occurrence. For the AK drill and blast tunnelling, the following remedial processes are considered;

Repair of drill jumbo: in the tunnelling cycle, the equipment breakdown that mainly affects cycle schedule is the breakdown of drill jumbo. Before drilling can continue, it requires that an extra process of repairing the drill jumbo be added to the normal drilling process. When it is completed, then drilling can proceed.

Attending to accidents: in the tunnelling cycle, accidents normally happen after blasting and ventilating arising from falling loose rocks. These may affects personnel and/or equipment found at the location of the accident. Before work can continue, it requires that an extra process of attending to the accident be added to the normal drilling process. When it is completed, then subsequent processes can proceed.

Solving labour remonstration: arising from poor working conditions which are amplified when accidents occur, many times workers tend to go on strike to demonstrate their discontent. Their actions may range from peaceful sit down strike to violent attacks on equipment and/or personnel which are very destructive and costly to the contractor. Any labour remonstration calls for immediate action from the by way of solving the remonstration and having work resume as soon as possible.

Delay in material delivery: Materials delivery is normally required after mucking has been completed for shotcreting, rock bolting and lining. Owing to the fact that the tunnelling activities have a finish to start relationship, a delay in material delivery whether excusable or non-excusable will require the contract to wait until the materials are delivered in order to complete the pending process (e.g. shotcreting) before the subsequent activities can proceed.

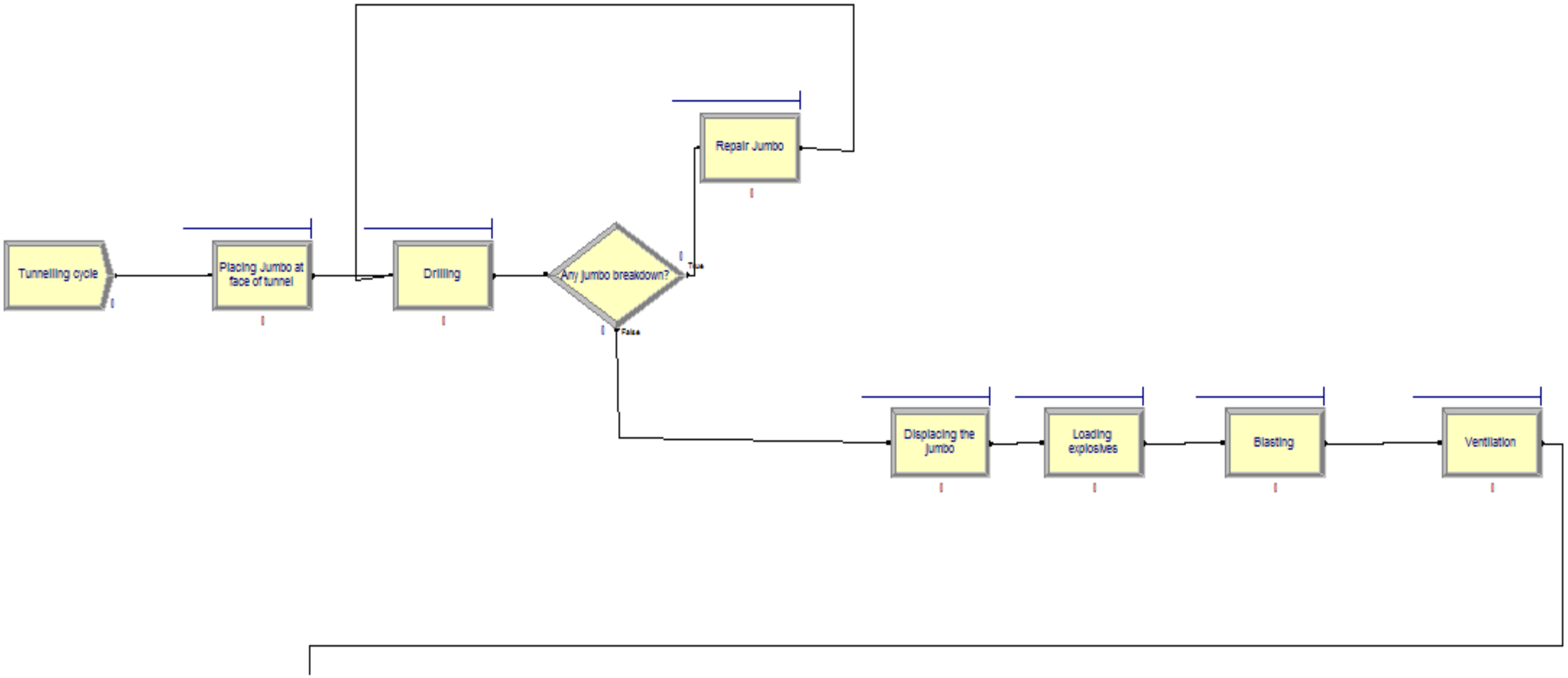


Figure 4.2-11 Overall drill and blast tunnelling process model developed by using ARENA simulation software

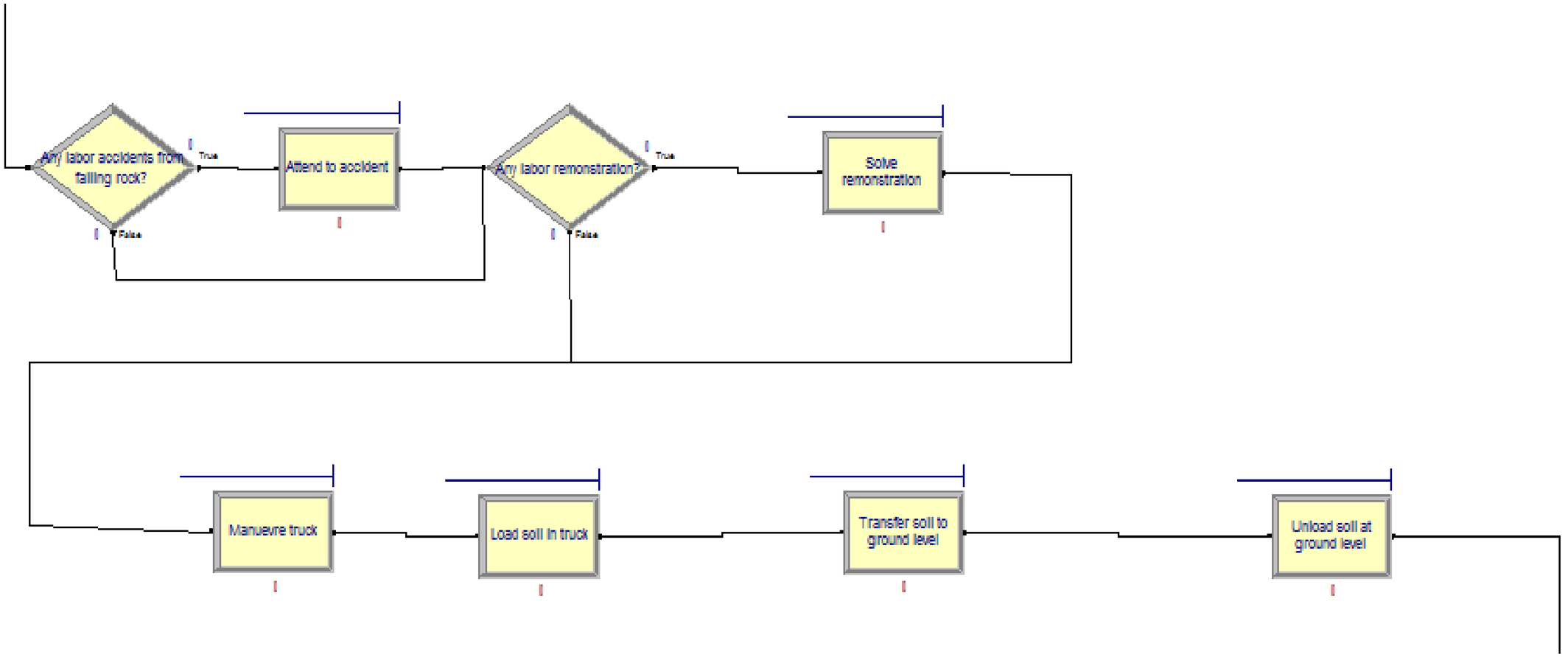


Figure 4.2-12 Overall drill and blast tunnelling operation model developed by using ARENA simulation software (cont..)

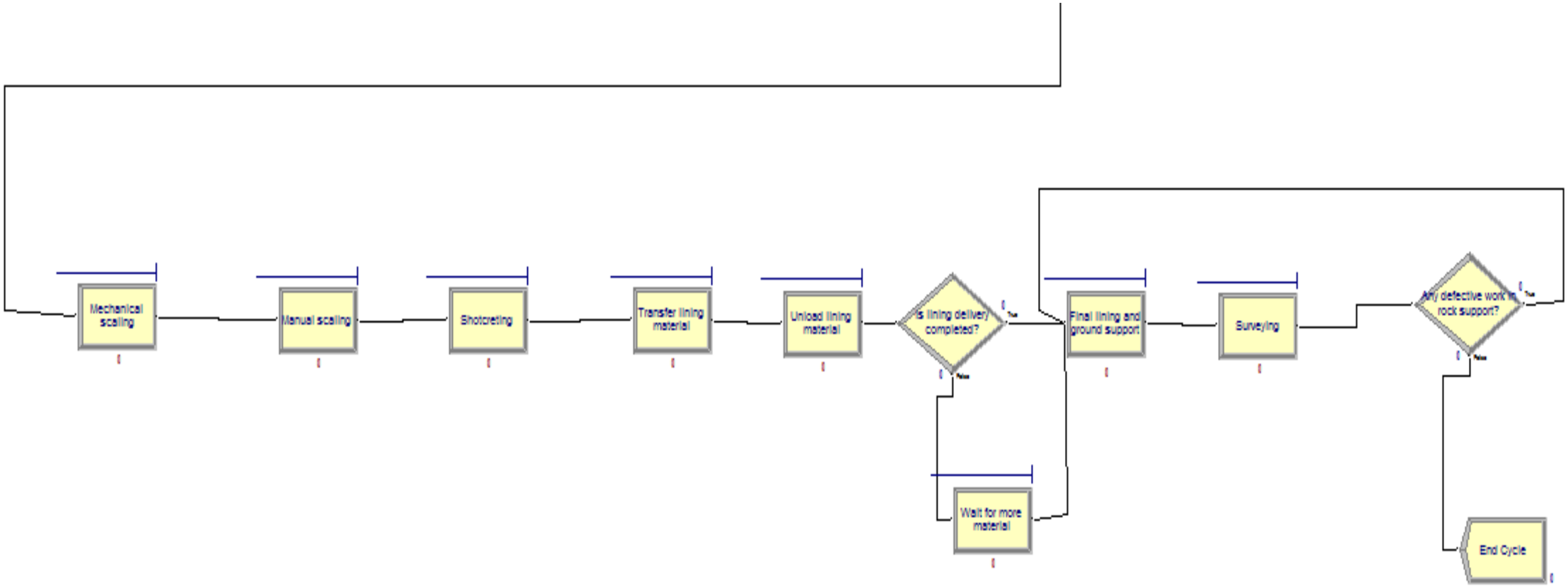


Figure 4.2-13 Overall drill and blast tunnelling operation model developed by using ARENA simulation software (cont..)

Rectification of defective work: If during inspection especially of the final lining and ground support it is discovered that that there is defective work, the contract is immediately required to remedy the defects before work may proceed. He may need to demolish and reconstruct or just some minor rectifications and modifications in the affected areas. In all, the contract will revisit the lining and ground support process.

B. AK drill and blast tunnelling performance oriented

This is important information to identify the input data and parameters based on the performance of the probabilities of risk occurrence. The risk input data was developed based on the variation of risk probabilities of occurrences for each identifies risk and applying the DEMATEL correlations to obtain the values for the spillover effects of that particular risk onto other risks.

Input data

The durations of the requisite durations for all the process and decision modules as imported from Monte Carlo Simulation and document reviews and are as in Figure 4.2-14 and 4.2-15 below.

Decide - Basic Process

	Name	Type	Percent True
1	Any labor accidents from falling rock?	2-way by Chance	17
2	Any labor remonstration?	2-way by Chance	0
3	Is lining delivery completed?	2-way by Chance	14
4	Any defective work in rock support?	2-way by Chance	14
5	Any jumbo breakdown?	2-way by Chance	0

Figure 4.2-14 Inputs to decision modules

The risk input data is as seen in Appendix 5-C

Process - Basic Process

	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Report Statistics
1	Placing Jumbo at face of tunnel	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	19	23	27	☑
2	Drilling	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	130	143	155	☑
3	Displacing the jumbo	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	15	18	20	☑
4	Loading explosives	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	43	57	69	☑
5 ▶	Blasting	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	24	27	30	☑
6	Ventilation	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	15	19	24	☑
7	Attend to accident	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	10	15	20	☑
8	Solve remonstration	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	240	480	960	☑
9	Manuevre truck	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	10	14	19	☑
10	Load soil in truck	Standard	Seize Delay Release	Medium(2)	2 rows	Triangular	Minutes	Value Added	40	55	65	☑
11	Transfer soil to ground level	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	25	33	40	☑
12	Unload soil at ground level	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	18	27	35	☑
13	Mechanical scaling	Standard	Seize Delay Release	Medium(2)	2 rows	Triangular	Minutes	Value Added	25	30	35	☑
14	Manual scaling	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	40	47	55	☑
15	Shotcreting	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	15	23	30	☑
16	Transfer lining material	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	7	10	14	☑
17	Unload lining material	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	13	19	25	☑
18	Final lining and ground support	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	35	45	54	☑
19	Wait for more material	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	10	25	40	☑
20	Surveying	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	13	21	30	☑
21	Repair Jumbo	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Minutes	Value Added	0	60	480	☑

Figure 4.2-15 Inputs to process modules

Data Distribution

The data distribution as determined under MCS is **Triangular Distribution.**

Run Simulation Model (ARENA)

After proper input data is obtained and its distribution selected, the next activity is running simulation model. However, before and during simulation running, it is necessary to check and identify the simulation modeling approaches such as simulation verification and validation. Checking simulation model with different criterion helps answer questions such as;

- Is the model defining properly the involved processes and risks?
- Are the work sequence and logical framework stated as areal-world operation?
- Are proper input data developed and fitted?

Accordingly, the subsequent section will address the questions in detail

Model verification

This was conducted to ensure that the model operates as intended. To verify the model, a single animated entity (Cycle) was created and followed through the model logic. It was observed that all the processes do not interfere with one another which correctly represented the finish to start relationships of the subsequent processes.

Simulation model validation

Model validation was conducted to ensure that the represented reality. This was conducted using parameter variability (Sensitivity Analysis) method. This technique consisted of changing the values of the risk input parameters of the model to determine the effect of output on the model's behavior. The same relations should occur in the model as in the real system. Risk parameters that were considered sensitive (i.e., cause significant changes in the model's behavior or output) were made sufficiently accurate prior to using the model by applying the correlations/weights obtained from DEMATEL Analysis.

In Figure 4.2-16 the relationship between the probability of occurrence of accidents and the tunnelling cycle duration is showed. There is almost no significant increment in minimum tunnelling cycle duration by increasing the probability of accident occurrence. It is also noticed that there is a linear relationship between probability of occurrence of accidents and average the tunnelling cycle duration while the maximum cycle duration also increases significantly with increase in probability of occurrence of accidents. Occurrence of accidents increases the amount of time required to attend to accident consequences. Accidents occurrence also leads to occurrence of other correlated risks in form of labour remonstration as a result of safety concerns and defective work arising from discontinuities in working patterns.

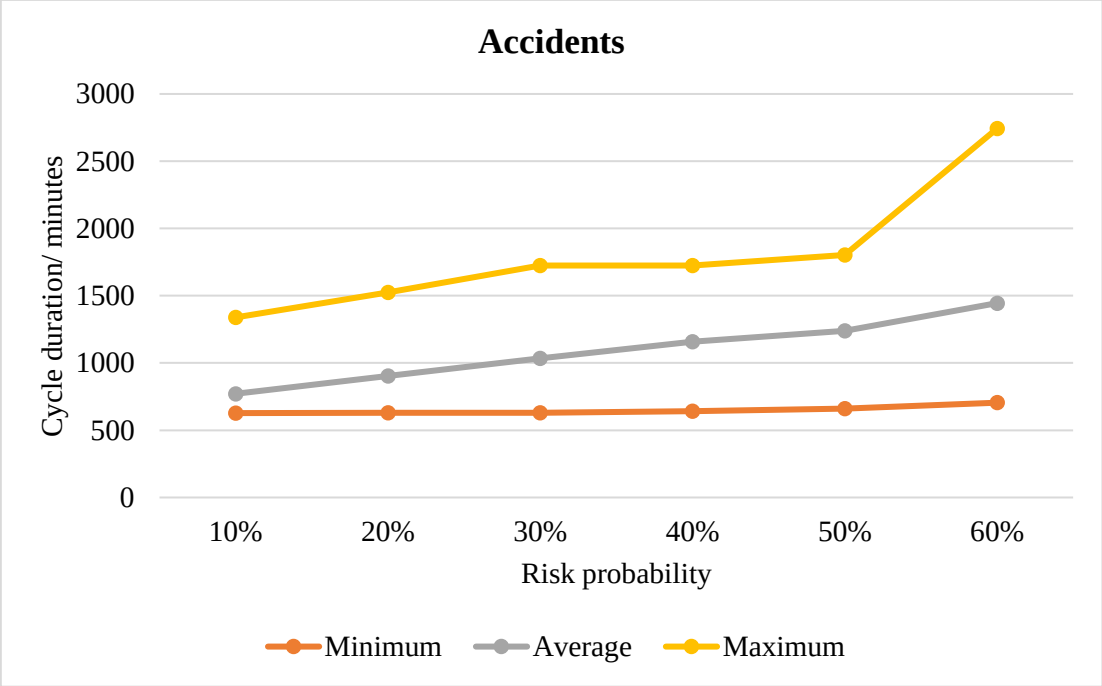


Figure 4.2-16 Sensitivity analysis on accident risk

In Figure 4.2-17, the relationship between the probability of occurrence of labour remonstration and the tunnelling cycle duration is showed. There is almost no significant increment in minimum tunnelling cycle duration by increasing the probability of labour remonstration occurrence. It is also noticed that there is an almost perfect linear relationship between probability of occurrence of a labour remonstration and the average tunnelling cycle duration while the maximum cycle duration also increases significantly with increase in probability of occurrence of labour remonstration. Occurrence of labour remonstration increases the amount of time required to attend to labour remonstration consequences. Labour remonstration occurrence also leads to occurrence of other correlated risks in form of accidents especially if the remonstration becomes violent, delay in material delivery due to unavailable machine operators and defective work arising from discontinuities in working patterns. All these activities require extra time to effect the requisite remedies.

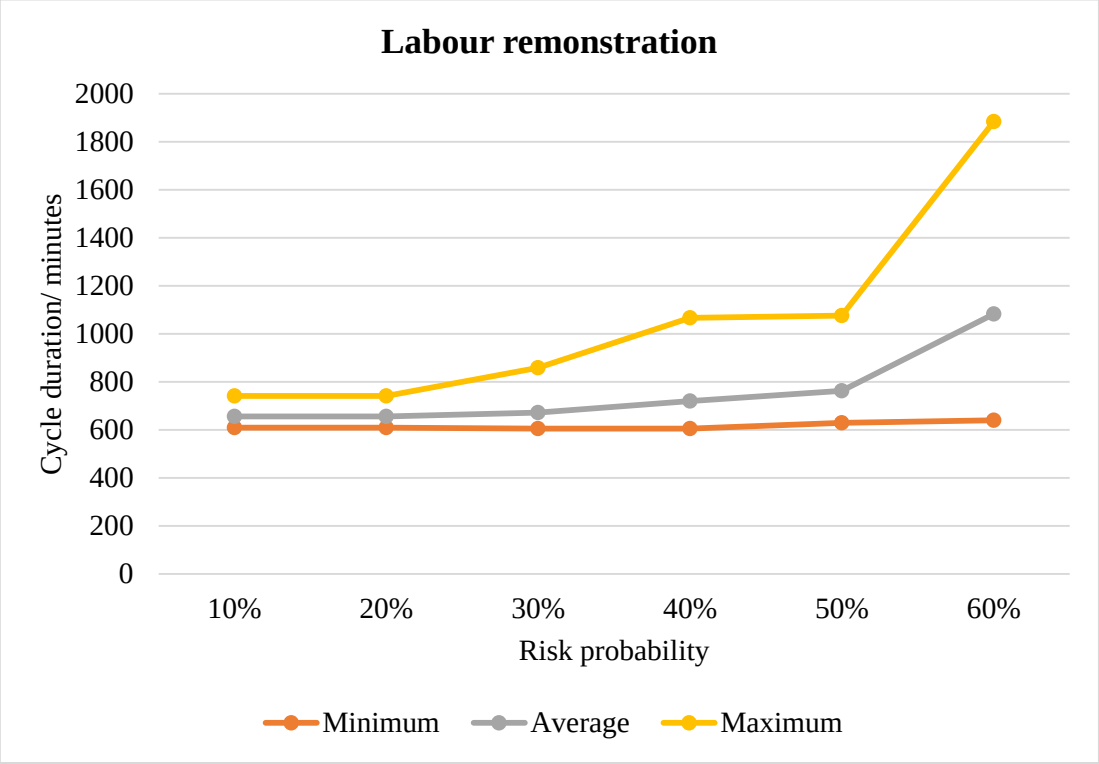


Figure 4.2-17 Sensitivity analysis on labour remonstration risk

In Figure 4.2-18, the relationship between the probability of occurrence of defective work and the tunnelling cycle duration is showed. There is no increment in minimum tunnelling cycle duration by increasing the probability of occurrence of defective work. It is also noticed that there is an almost linear relationship between probability of occurrence of defective work and the average tunnelling cycle duration while the maximum cycle duration initially increases between 10-20% after which it remains constant with increase in probability of occurrence of defective work. Occurrence of defective work increases the amount of time required to rectify the defective work which interventions may range from simple remedial work and other times include total demolition and reconstruction. Defective work occurrence also leads to occurrence of other correlated risks in form of accidents especially where the defective work is a safety risk as well. All these activities require extra time to effect the requisite remedies.

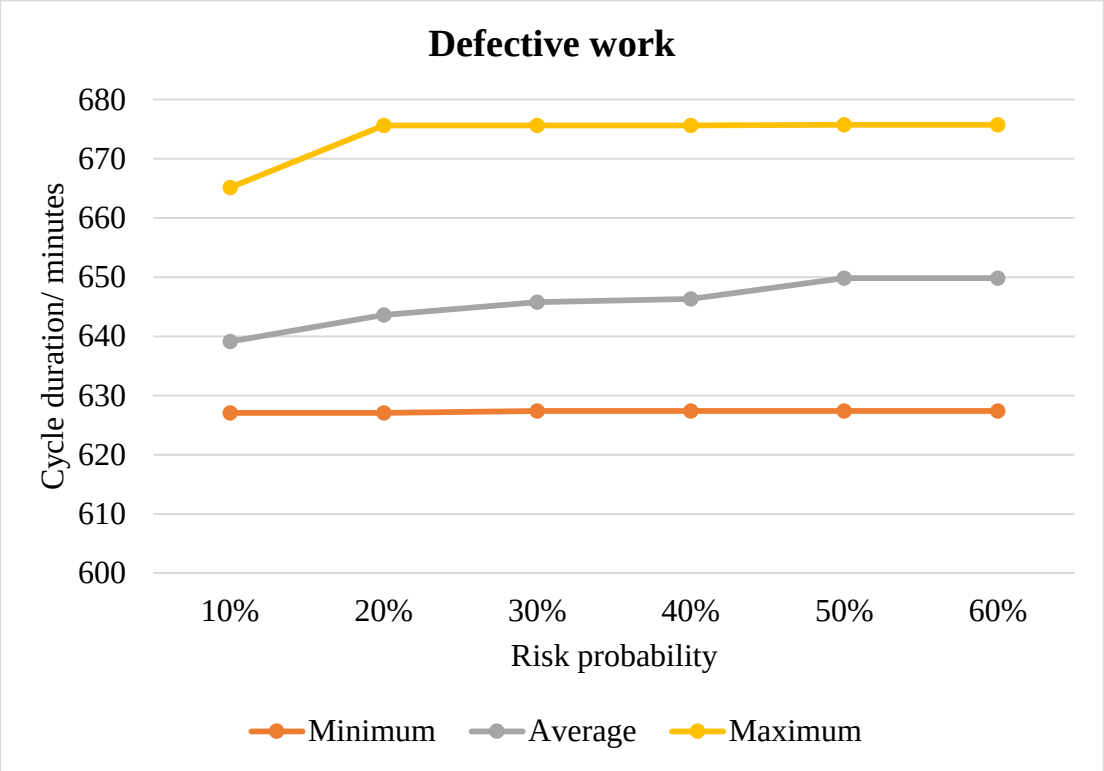


Figure 4.2-18 Sensitivity analysis on defective work risk

In Figure 4.2-19, the relationship between the probability of occurrence of delay in material delivery and the tunnelling cycle duration is showed. Majorly, the minimum tunnelling cycle duration is constant with increase in the probability of occurrence of delay in material delivery. It is also noticed that there is an almost linear relationship between probability of occurrence of delay in material delivery and the average tunnelling cycle duration while the maximum cycle significantly shows and increase with increase in probability of occurrence of delay in material delivery. Occurrence of delay in material delivery increases the amount of time required to conduct activities such as shotcreting due to the waiting time incurred. Delay in material delivery occurrence also leads to occurrence of other correlated risks in form of accidents especially where the contractors tries to speed up activities to recover lost time and also where the tunnel standup time is exceeded leading to eventual tunnel collapse. Excessive delay in material delivery may force the contractor to reduce pay days for casual labour in order to reduce costs which would ultimately result in labor remonstrations. The delay in material delivery may also result in defective work arising from discontinuities in construction cycles. All these activities require extra time to effect the requisite remedies.

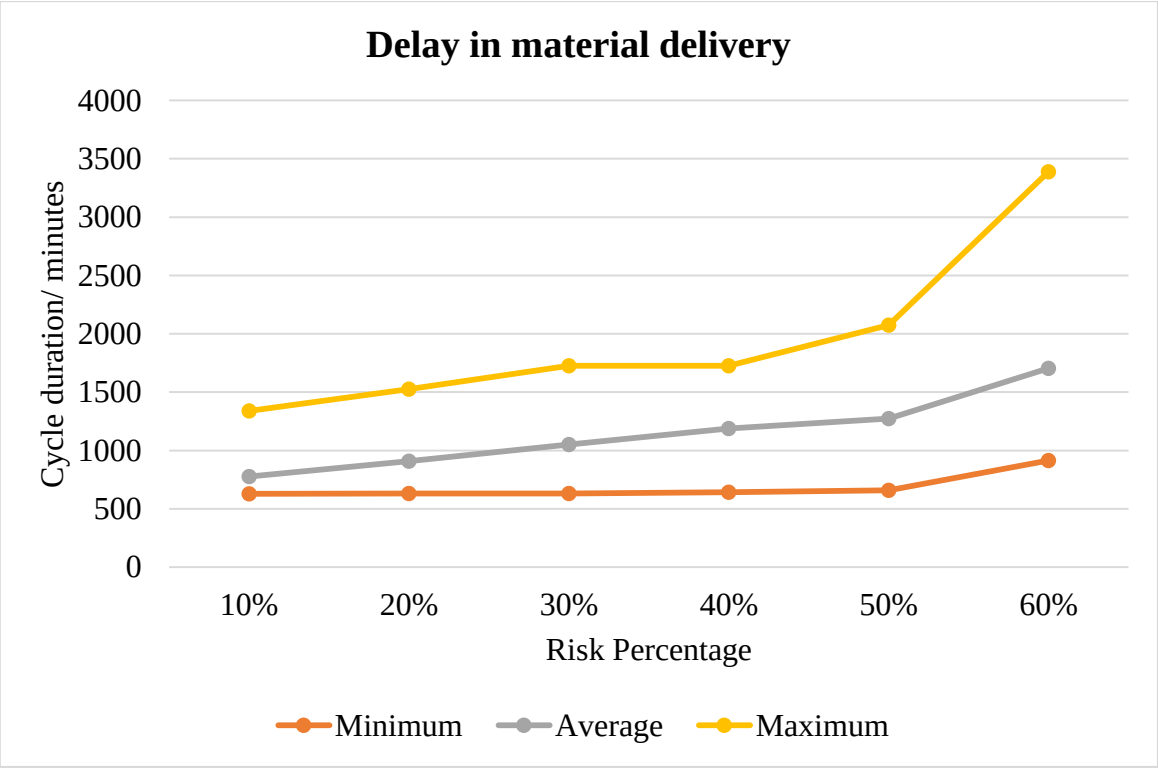


Figure 4.2-19 Sensitivity analysis on delay in material delivery risk

In Figure 4.2-20 the relationship between the probability of occurrence of plant and machine failures and the tunnelling cycle duration is showed. Majorly, the minimum tunnelling cycle duration is constant with increase in the probability of occurrence of plant and machine failures. It is also noticed that there is a linear relationship between probability of occurrence of plant and machine failures and the average tunnelling cycle duration while the maximum cycle significantly shows and increase with increase in probability of occurrence of plant and machinery failures. Occurrence of plant and machine failures increases the amount of time required to conduct activities such as drilling, shotcreting and rock bolting due to the repair time required. Delay due to plant and machine failures occurrence also leads to occurrence of other correlated risks in form of accidents especially where the contractors tries to speed up activities to recover lost time and also where the tunnel standup time is exceeded leading to eventual tunnel collapse. Excessive waiting due to plant and machine failures may force the contractor to reduce pay days for casual labour in order to reduce costs which would ultimately result in labor remonstrations. The plant and machine failures may also result in defective work arising from discontinuities in construction cycles. All these activities require extra time to effect the requisite remedies.

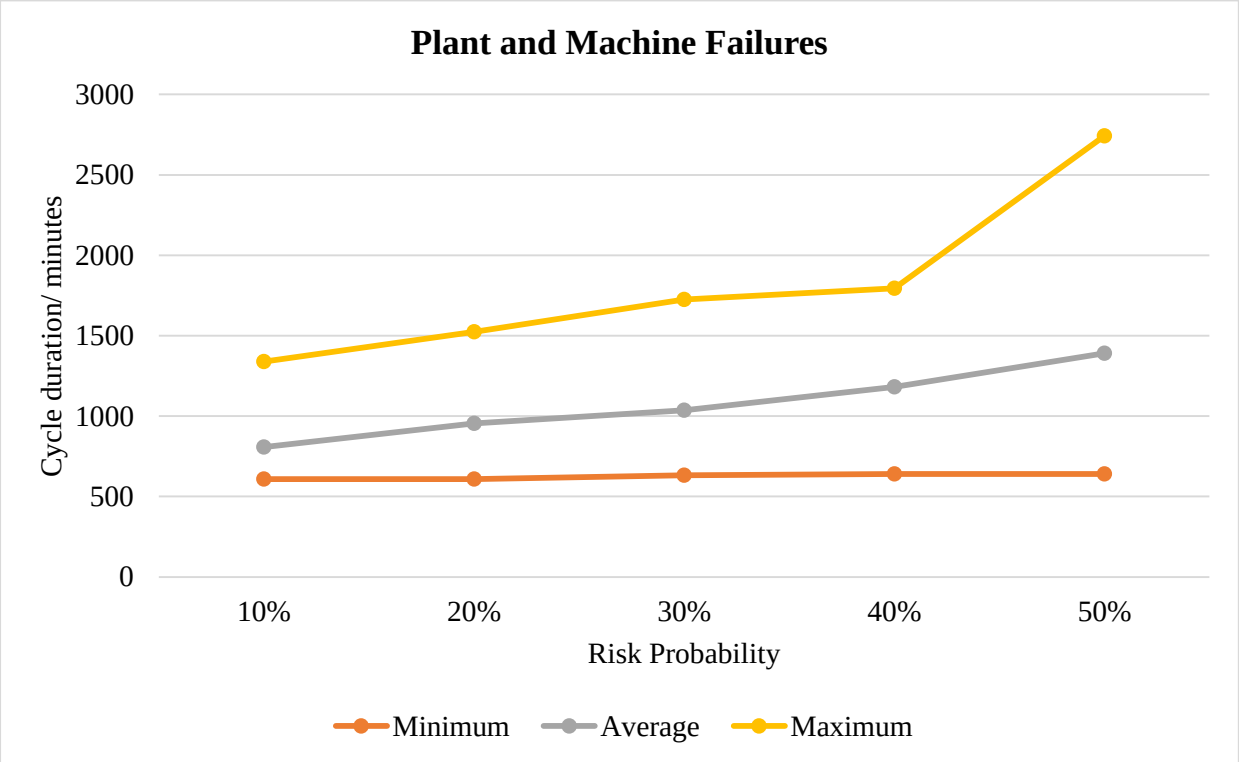


Figure 4.2-20 Sensitivity analysis on plant and machinery failure risk

Experimental design

Identification of significant factors

By performing the sensitivity analysis the effect of each individual variable on the tunnelling cycle duration is shown. Also the impact on the tunnelling cycle duration of the variables compared to each other may be assessed.

Sensitivity analysis carried out in the simulation model of the Awash-Kombolcha tunnels has shown the effect of tunnelling risks occurrence on the tunnelling cycle duration of the project. For tunnel excavated by drill and blast the analysis has shown that the risk variables 'accidents', 'plant failure' and 'delayed material delivery' have the biggest impact on the minimum, average and maximum tunnelling duration. The sensitivity analysis has also shown that the variables 'labour remonstration' and 'defective work' are less significant. Figure 4.2-21 to 4.2-23 below show the results of the sensitivity analysis related to the Awash-Kombolcha tunnels excavated by conventional drill and blast.

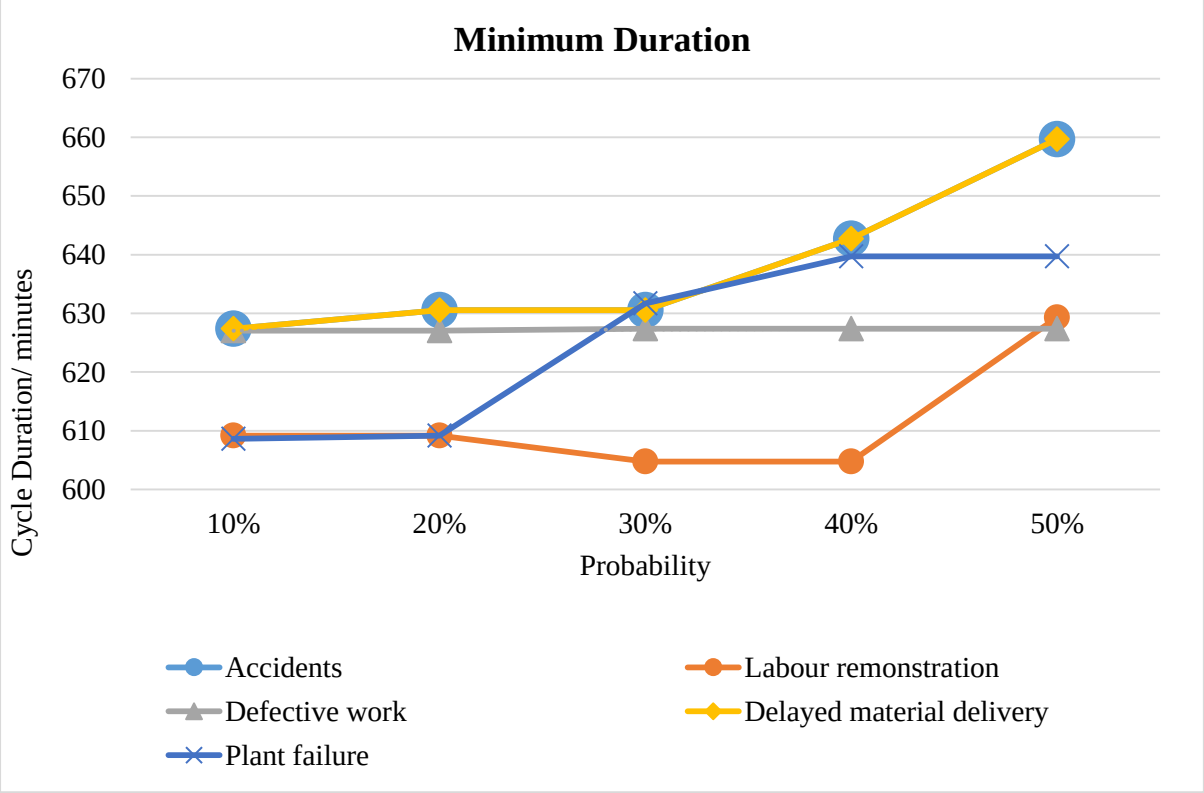


Figure 4.2-21 Sensitivity analysis results for minimum durations

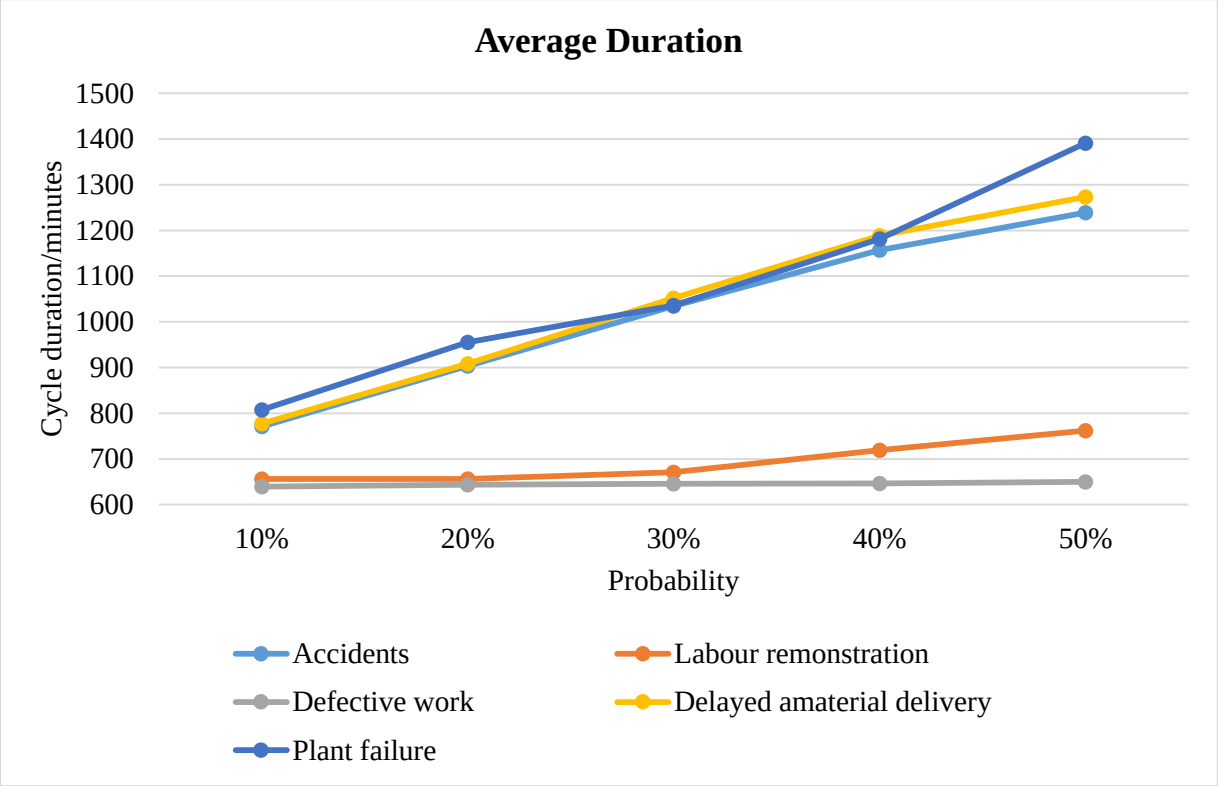


Figure 4.2-22 Sensitivity analysis results for average durations

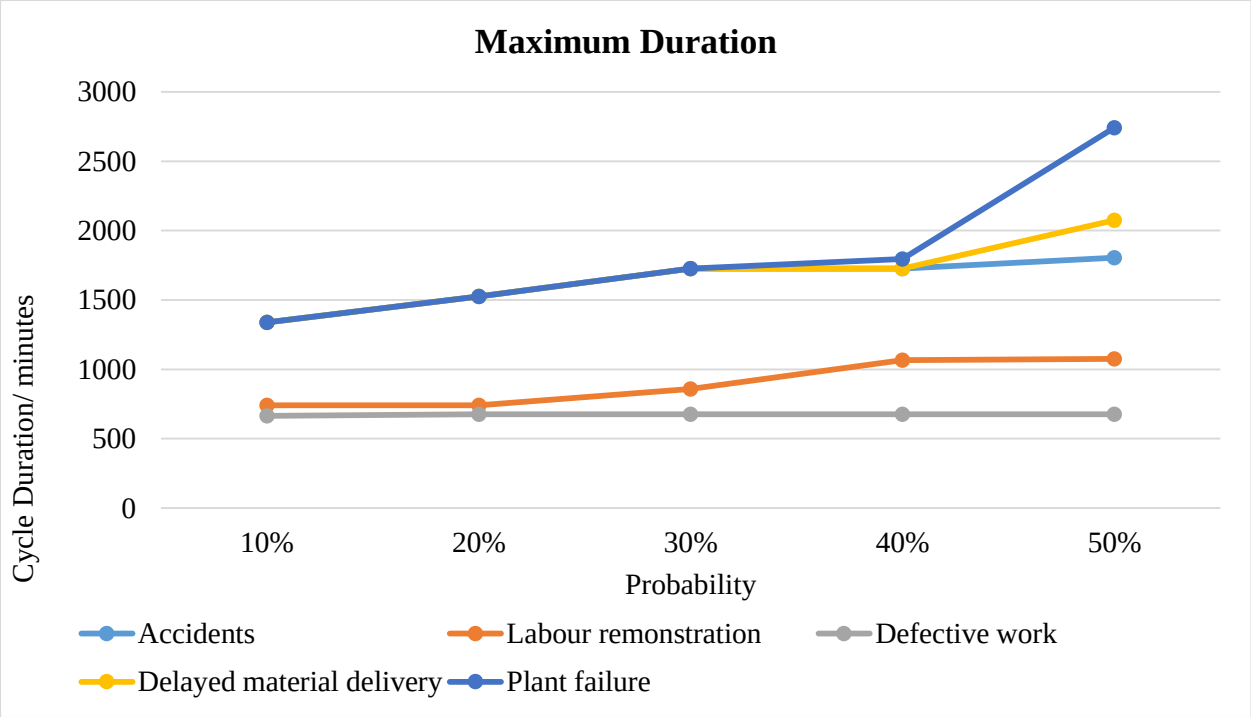


Figure 4.2-23 Sensitivity analysis results for maximum duration

From Figure 4.4-22, the DES maximum cycle duration is determined as **1725.53 minutes** at 30% probability of occurrence.

4.2.7 Validation of Severity Analysis, MCS and DES results

Actual cycle time calculations

Regression analysis is a statistical tool for the investigation of the relationships between variables. In this research regression analysis is applied to show the relation between the length of the tunnel and respectively the cycle time. Figure 4.2-24 shows the linear regression analysis of collected data in Appendix 7 for the cycle time calculations of the tunnelling by drill and blast.

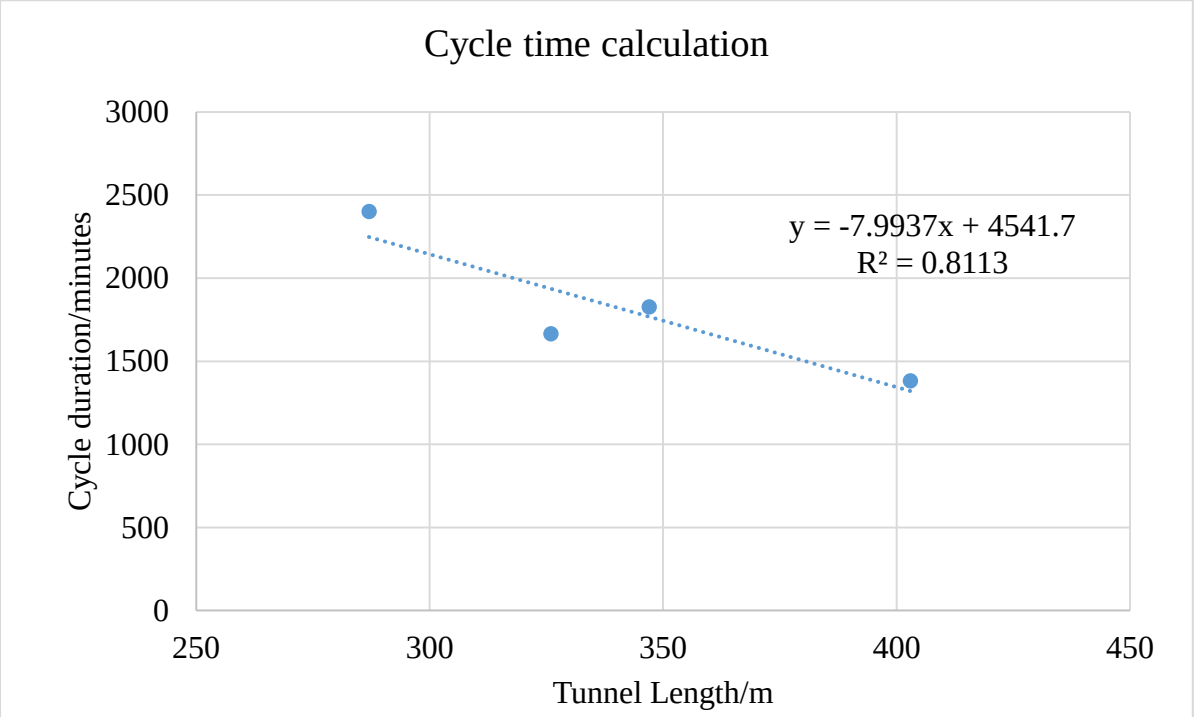


Figure 4.2-24 Cycle time calculation for Awash-Kombolcha tunnelling project

The graph in Figure 4.2-24 makes clear that there is a (linear) relationship between the tunnel length and the total cycle time of the construction processes. It can be observed that the longer the tunnel length, the less the cycle duration. This can be attributed to the improvement in productivity and processes with the number of repetition of the cycles. The more the cycles, the easier it is to repeat the processes hence increasing productivity and control of risks. Whereas increasing tunnel length would have increased the cycle duration due to increased

length of transfer of materials, the length of the tunnels is relatively not big enough, for the material transportation time durations of the trucks, to make a significant impact on the total cycle time of the tunnelling cycle. The increasing time durations of the transportation activities are an insignificant part of the total cycle time of the tunnelling processes.

In the graph in Figure 4.2-24, the cycle time with its R^2 value, determined by regression analysis, is described for the simulation model. The value of R^2 indicates the proportion of variability in a set of data that is accounted for the statistical model. It provides a measure of how well future outcomes are likely to be predicted by the model. Values of R^2 nearby 1 mean that there is a significant relationship between the variables. Hence, the equations determined by linear regression analysis are good predictors for the calculations of cycle time. For the Awash-Kombolcha tunnelling sub-projects, the cycle time can be determined using Equation 4.2-2 developed by regression analysis.

$$Cycle\ time\ (minutes) = \ 4541.7 - 7.9937L \qquad \text{……Equation 4.2-2}$$

Where L= Tunnel length (m)

$$Total\ actual\ tunnelling\ duration\ (minutes) = \ cycle\ time * No.of\ cycles \qquad \text{……Equation 4.2-3}$$

All models are wrong because they cannot exactly represent an actual situation due to the limitations in size. However, the accuracy of the model depends on the accuracy of the estimated inputs.

Since the prediction models all based on single tunnelling cycles, it was assumed that the risk occur in similar ways for all the cycles involved to completion of the entire tunnel.

The prediction models were validated by comparing the actual cycle duration for Tunnel 3, 4. 6 and 7 with the model maximum value predicted at a point of intersection of the lines for maximum duration graphs (i.e at probability 30%) using RMSE in Equation 4.2-4.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - A_i)^2}{n}} \qquad \text{….Equation 4.2-4}$$

Where: P -predicted duration, A - actual duration and n - number of tunnels.

Validation of results involved the comparison of the Total tunnelling duration results from Severity Analysis, Monte Carlo Simulation and DES as in Table 4.2 -20 below.

From Table 4.2-20 below, the following are observed:

Generally: None of the models perfectly predicted the actual tunnelling durations. This is attributed to the fact that the accuracy of the outcome mainly depends on the accuracy of input data and the model size. Since most of the data is obtained from interviews, it is subject to respondent's biasness thereby creating errors.

Severity Analysis: Had the highest RMSE value of **59,369.76** minutes**.** This makes the method totally unreliable/invalid since it totally depends on expert's judgement.

Monte Carlo Simulation: Applying MCS gave results which were much more accurate the Severity Analysis with and RMSE value of **24,050.65** minutes. These results compare more with the actual durations obtained on the project.

Discrete Event Simulation: Applying DES gave results which were the most accurate of all the applied prediction methods with an RMSE of **23,244.91** minutes. This could be attributed to the fact that it's a modification of MCS giving it more accuracy.

Considering the difference in actual and predicted results, it can be seen that there is a huge difference in results for tunnels for tunnels of length >500m which significantly affected RSME results for all the models. This could be attributed to the fact that the longer the tunnel, the more erroneous the assumption of similar risk occurrences per cycle becomes.

Table 4.2-20 Validation of Severity, MCS and DES results

				Calculated/Simulated durations (minutes)			**Model Accuracy (validity) by RSME**		
Tunnel	**Length (m)**	**Number of cycles (5m per cycle)**	**Actual Tunnelling Duration (minutes)**	**Severity**	**MCS**	**DES**	**(Actual Tunnelling Duration - Calculated duration)**		
							Severity	**MCS**	**DES**
Tunnel No.3	347	69.4	122,691.30	175,651.40	114,154.67	119,751.78	2,804,772,685.60	72,873,938.05	8,640,738.68
Tunnel No.5	403	80.6	106,411.26	203,998.60	132,577.33	139,077.72	9,523,289,837.79	684,663,358.45	1,067,097,782.72
Tunnel No.6	326	65.2	126,211.15	165,021.20	107,246.18	112,504.56	1,506,220,154.87	359,670,153.86	187,870,657.68
Tunnel No.7	287	57.4	129,006.96	145,279.40	94,416.11	99,045.42	264,792,142.78	1,196,527,107.12	897,694,055.35
RMSE							**59,369.76**	**24,050.65**	**23,244.91**

Conclusion

Based on the results of the analysis, tunnelling construction managers would be able to evaluate the impact of risk decisions on the final duration of the tunnelling project. It is useful to know what will happen if the magnitude of one of the controllable tunnelling risks is changed. The results of the sensitivity analysis can be used to make decisions regarding scheduling and planning of tunnelling processes for drill and blast tunnelling projects.

4.2.8 Comparative analysis

Aspect	SEVERITY	MONTE CARLO SIMULATION	DISCRETE EVENT SIMULATION (Using ARENA)
1. Description	• Analyses risks through single point estimates of potential impacts	• Analyses risks through probability distributions of potential impacts	• Discrete event simulation is a particular application of Monte Carlo simulation. It is the simulation of systems which are mainly driven by events which occur stochastically in points in time. • Discrete Event simulation represents the status of entities moving through a series of steps.
2. Requirements	• Requires increased investment of time to develop single-point probability and estimated impact of each identified risk	• Requires further increased investment of time to develop three-point probability and estimated impact of each identified risk • Requires additional time and sometimes resources to facilitate an	• Requires further additional time beyond MCS to build a process map and eventual model, run simulations and analyze the quantitative outputs.

Aspect	SEVERITY	MONTE CARLO SIMULATION	DISCRETE EVENT SIMULATION (Using ARENA)
	• Requires a lot of tunnelling experience to increase chances of better estimates • Requires proper pre-defined estimates of schedule impacts to be applied.	outsourced expert to perform and analyze the quantitative simulations	
3. Benefits	• Provides probability x impact matrix • Generates prioritized list of risks • Calculates expected value for contingency allocation of time	• Provides cumulative probability distribution • Increases probability of meeting project targets • Project duration is based upon desired level of certainty	• Flowchart modeling methodology includes a large library of pre-defined building blocks to model your process without the need for custom programming • Complete range of statistical distribution options to accurately model process variability • Statistical analysis and report generation

Aspect	SEVERITY	MONTE CARLO SIMULATION	DISCRETE EVENT SIMULATION (Using ARENA)
			• Realistic 2D and 3D animation capabilities to visualize results beyond numbers
4. Results	• Make go/ no-go decisions based upon expected values • Prioritizes risks to manage • Communicates risks intuitively and visually • Allocates resources to manage and mitigate the most significant risks	• Clearly communicates schedule uncertainty • Determines the impact of risk events on project performance • Determines the likelihood of achieving project outcomes • Gives an output the likely delay due to risk occurrence. • Directly updates the CPM schedule to show the impacts of risk occurrence on schedule	• The outputs are discrete estimates. • Determines the impact of risk events on project performance • Outputs the total duration required to complete a cycle.
5. Limitations	• One point estimate doesn't include the uncertainty inherent in the risk estimate	Is dependent on validity of information input into the model and complexity of the model	• Is dependent on validity of information input into the model and complexity of the model

Aspect	SEVERITY	MONTE CARLO SIMULATION	DISCRETE EVENT SIMULATION (Using ARENA)
	• Is unable to communicate the collect impact of risks to achieve project targets		• Inputting probabilities of risk occurrence as a single estimate does not consider the inherent risk in probability estimations. • It's a lengthy process of risk analysis

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Summary

This thesis aimed at developing a probabilistic model for time impact analysis that can be used to forecast the amount of delay that will arise from occurrence of some major risks in conventional tunnelling using simulation as a capable tool. The process involved the identification of intolerable risks to schedule in conventional tunnelling, determination of risks correlations using DEMATEL, estimation the delay arising from occurrence of the risks using Severity Analysis, Monte Carlo and Discrete Event Simulation and finally conducting a comparative analysis of risk modelling techniques. The start of this thesis established the objectives, the approach to be followed during the implementation of research. It was determined that there is a gap in current literature relating to transcribing qualitative expressions into quantitative measurements in the absence of historical data as well as in the quantification of impact of risk occurrence. Moreover, other than for academic purposes, DES has barely been used for schedule analysis. Engineers prefer to use quick and simple severity analysis which is highly inaccurate.

In order to understand the objectives, an example of the process of risk analysis was examined through a case study, allowing for the reader to understand the entire process of risk analysis and delay prediction using the various methods and merits and level of accuracy expected by using one over the other.

To optimize the input used for risk parameters, a survey was conducted soliciting information on likelihoods, impacts and the correlations between risks. For confidence, results were gained from both the Contractor (3 interviewees) and Consultant's (2 interviewees) personnel to allow for verification of the information given.

In order to demonstrate the credibility of the model under development, Severity Analysis and Monte Carlo simulation experiments were conducted to understand the sensitivity of the probability of occurrence of project risks to schedule duration impact. A DES Model was then developed in ARENA software and a validation of results for all the three methods conducted against the actual tunnelling durations for four tunnels from the project.

The results showed that DES with inputs from Monte Carlo Simulation and DEMATEL analysis was a superior method of predicting delay. However Monte Carlo Simulation favorably compared to DES. Severity Analysis was the most invalid of the 3 models with the largest RSME but could be useful for preliminary quick assessment just to give an idea of the risks that pose the biggest impact on the project.

5.2 Conclusions

1. Severity analysis should only be used for simple projects to just give an indication of the risks to mitigate but not for delay prediction purposes.
2. The accuracy of Monte Carlo and Discrete Event Simulation can be increased by collecting data from more experts to further reduce the margin of error.
3. Monte Carlo Simulation and DES models developed can be used comfortably for tunnels of length less than 500mm. However, for tunnels of length >500m, the methods should be used with modifications.

5.3 Recommendations for future work

Future work is recommended to be carried out in the following aspects:

1. Developing models that incorporate the entire length of the tunnel within the model.
2. Developing models that consider the dynamic nature of the risks within each cycle
3. Similar work can be conducted for tunnels on a different case study to determine how the outcome compares.
4. Models involving all the identified risks can be developed to check whether the results would improve significantly.

REFERENCES

AACE, I. (2011). *Integrated Cost And Schedule Risk Analysis Using Monte Carlo Simulation of a CPM Model.* USA: AACE International, Inc.

AbouRizk, M. S., & Dozzi, S. P. (1993). Application of computer simulation in resolving construction disputes. *Journal for Construction Engineering and Management, ASCE, 2*(119), 355.

AbouRizk, S. M. (2008). *Risk Analysis for Construction Projects.* Alberta.

Addis, M. (2014). *A Study on Construction Contract Risk Management Practices in Ethiopian Building Construction Projects.* Addis Ababa: Addis Ababa University.

Ali, S. A., Sorooshian, S., & Kie, C. J. (2016). Modelling for Causal Interrelationships by DEMATEL. *Contemporary Engineering Sciences, Vol. 9*, 403 - 412.

Ameh, O. (2011). Study of relationship between time overrun and productivity on construction sites. *International Journal of Construction Supply Chain Management 1(1)*, 56-67.

Amiri, M. (2011). Developing a DEMATEL method to prioritize distribution centers in supply chain. *Management Science Letters*(1), 279–288.

Amiri, M., Sadaghiyani, J. S., Payani, N., & Shafieezadeh, M. (2011). Developing a DEMATEL method to prioritize distribution centers in supply chain. *Management Science Letters, 1*, 279-288.

Brox, D. (2017). *Practical Guide to Rock Tunneling.* London: CRC Press.

Charoenngam, C., & Yeh. (1999). Contractual risk and liability sharing in hydropower construction. *International Journal of Project Management*, Vol 17, No 1, pp 29-37.

Corporation, E. R. (2017). *Awash -Kombolcha -Hara Gebeya Railway Project Summary and Status Report.* Addis Ababa: ERC.

David Chapman, N. M. (2010). *Introduction to Tunnel Construction.* Abingdon: Spon Press.

Emran, H. A. (2017). *A Study on Development of a Conceptual Risk Management Framework: A Case Study on Addis Ababa City Roads Authority.* Addis Ababa: Addis Ababa University.

Eskesen, S. D. (2006). *ITA WG 2 – Guidelines for Tunnelling Risk Assessment.* Seoul: COWI A/S.

Eskesen, S. D., Tengborg, P., Kampmann, J., & Veicherts, T. H. (2004). Guidelines for tunnelling risk management: International. *The International Tunnelling Association (ITA)* (pp. 217-237). Lausanne: Elsevier Ltd.

Farid Ghazali and H.C. Wong. (2013). Risk Ranking for Tunnelling Construction Projects in Malaysia. *KICEM Journal of Construction Engineering and Project Management*, 29-36.

Fontela, E., & Gabus, A. (1974). *DEMATEL, Innovative Methods, Report No.2, Structural Analysis of the World Problematique.* Geneva: Batelle Geneva Research Institute.

Forum, R. A. (1997). *Guiding Principles for Monte Carlo Analysis.* Washington: U.S. Environmental Protection Agency.

Getachew, T. (2009). *Design Risk Management in Ethiopian Federal Road Projects.* Addis Ababa: Addis Ababa University.

Getachew, Y. (2014). *The Practice of Construction Risks Management through Insurance in the Ethiopian Federal Roads Projects.* Addis Ababa: Addis Ababa University.

Lee Yong Siang, F. E. (2017). General Risks For Tunnelling Projects: An Overview. *AIP Conference Proceedings 1892, 080004 (2017); doi: 10.1063/1.5005730.*

Likhitruangsilp, V. (2003). *A risk-based dynamic decision support system for tunnel construction.* Department of Civil Engineering. Michigan: University of Michigan.

Milka, H. (2016). *Decision Support Mechanism for Risk Allocation in Private Real Estate Purchase Agreements.* Addis Ababa: Addis Ababa University.

Nejbel, M. A. (2014). *A study on planning and scheduling in federal road projects of Ethiopia: Causes of non-excusable delay in selected projects.* Addis Ababa: Addis Ababa University.

Obeidat, A., Al-Barqawi, H., Zayed, T., & Amer, M. (2006). Productivity of tunnel Construction using road-headers. *First International Construction Specialty Conference*, (pp. 1-10).

Pamukcu, C. (2015). *Analysis and management of risks experienced in tunnel construction pp.273.* Buca: Acta Montanistica Slovaca.

PMBOK. (2008). *A guide to the Projecr Management Body of Knowledge, PMBOK GUIDE* (Fourth ed.). Pennyslavia: Project Management Institute.

Rausand, M. (2011). Introduction to Risk Assessment. In *Risk Assessment; Theory, Methods and Applications* (pp. 4-6). Trondheim, Norway: John Wiley & Sons Inc.

Ruwanpura, J. Y. (2001). *Special purpose simulation for tunnel construction operations, PhD Thesis.* Alberta: Department of Civil Engineering and Management, Edmonton.

Salling, K. B. (n.d.). *Risk Analysis and Monte Carlo Simulation within Transport Appraisal.* Lyngby: http://www.ctt.dtu.dk/group/dmg/.

Shannon, R. E. (1992). Introduction to simulation. *Proceedings of the 1992 Winter Simulation, 65-73.*

Shieh, J. I., Wu, H. H., & Huang, K. K. (2010). A DEMATEL method in identifying key success factors of hospital service quality. *Knowledge Based System, 23*(no. 3), 277-282.

Spackova, I. (2012). *Risk management of tunnel construction projects.* Prague.

Steuer, R. E. (1986). *Multiple Criteria Optimization: Theory, Computation and Application.* New York: Wiley.

Summers, J. (2000). Analysis and management of mining risks. *Proceedings of the MassMin 2000, pp. 63-64,.* Australia.

Temsegen, T. (2015). *Right of Way Risk Management of Road Construction Projects in Urban Areas, A Case Study of Addis Ababa.* Addis Ababa: Addis Ababa University.

Tesfamichael, G. (2015). *Development of Design Aid for Tunnel Lining Design using Analytical Method (Continuum).* Addis Ababa: Addis Ababa University.

Vanegas, J. A., & Halpin, D. W. (1993). Use of Construction Simulation in Claims Analysis. *Proceedings of the Fifth International Conference Computing in Civil and Building Engineering.* California.

Vose, D. (2002). *Risk Analysis - A Quantitative Guide. 2nd Edition.* England: John Wiley & Sons Ltd.

Wakjira, T. (2011). *Risk Factors Leading to cost overrun in Ethiopian Federal roads construction projects and its consequences.* Addis Ababa: Addis Ababa University.

APPENDICES

APPENDIX 1: QUESTIONNAIRES

APPENDIX 2: QUALITATIVE ANALYSIS TABLES

APPENDIX 2-A LIKELIHOOD AND CONSEQUENCE REFERENCE TABLES

Likelihood		Consequence	
Descriptor	**Explanation**	**Descriptor**	**Explanation**
A. Highly Likely	Almost certain that it will happen, very frequent occurrence	A. Catastrophic	The impact is totally unacceptable to the project
B. Likely	More than 50-50 chance	B. Major	Serious threat to the organization, public etc.
C. Occasional	Less than 50-50 chance	C. Significant	Considerably affects schedule
D. Somewhat likely	Small likelihood, but could well happen	D. Moderate	Moderately effects schedule
E. Very unlikely	Not expected to happen	E. Minor	Trivial effect on schedule
F. Extremely unlikely	Just possible, but would be very surprising		

APPENDIX 2-B: QUALITATIVE ANALYSIS REFERENCE SCALE

	CONSEQUENCE				
FREQUENCY/LIKELYHOOD	**Catastrophic**	**Major**	**Significant**	**Moderate**	**Minor**
Highly likely	Intolerable	Intolerable	Critical	Critical	Serious
Likely	Intolerable	Critical	Critical	Serious	Important
Occasional	Critical	Critical	Serious	Serious	Important
Somewhat likely	Critical	Serious	Serious	Important	Acceptable
Very unlikely	Serious	Serious	Important	Important	Acceptable
Extremely unlikely	Serious	Important	Important	Acceptable	Negligible

APPENDIX 2-C: QUALITATIVE ANALYSIS INTERVIEW DETAILS COMBINED FOR CONTRACTOR AND CONSULTANT EXPERTS

Hazard Number	Hazard	Consequence			Likelihood		
		Contractor	Consultant	Combined	Contractor	Consultant	Combined
1	Accidents	Minor	Major	Significant	Highly likely	Highly likely	Highly likely
2	Labour remonstration/ disputes	Major	Major	Major	Occasional	Highly Likely	Likely
3	Political change	Catastrophic	Significant	Major	Somewhat likely	Somewhat likely	Somewhat likely
4	Stop work order/Defective work	Major	Major	Major	Occasional	Highly likely	Likely
5	Delay in material delivery	Major	Major	Major	Occasional	Highly likely	Likely
6	Plant and machinery failure	Minor	Major	Significant	Highly likely	Highly likely	Highly likely
7	Manual tasks	Minor	Significant	Moderate	Occasional	Highly likely	Likely
8	Subsurface geological conditions	Moderate	Moderate	Moderate	Likely	Likely	Likely

Hazard Number	Hazard	Consequence			Likelihood		
		Contractor	Consultant	Combined	Contractor	Consultant	Combined
9	Subsurface hydrogeological conditions	Moderate	Moderate	Moderate	Likely	Likely	Likely
10	Acts of God (earthquake, fire etc.)	Catastrophic	Catastrophic	Catastrophic	Somewhat likely	Very unlikely	Somewhat likely
11	Delayed dispute resolution	Moderate	Significant	Moderate	Likely	Occasional	Likely
12	Change order negotiation	Significant	Significant	Significant	Likely	Somewhat likely	Occasional
13	Delayed payment on contract and extras	Major	Significant	Significant	Likely	Somewhat likely	Occasional
14	Late drawings and instructions	Major	Moderate	Significant	Likely	Somewhat likely	Occasional
15	Delayed site access	Major	Moderate	Significant	Somewhat likely	Very unlikely	Very unlikely

APPENDIX 3: SEVERITY ANALYSIS TABLES

APPENDIX 3-A: PROBALITY AND CONSEQUENCE RATINGS

PROBABILITY RATING		
Descriptor	**Probability**	**Rating**
Highly Likely	>70%	6
Likely	50 - 70%	5
Occasional	15% - 50%	4
Somewhat likely	1% - 15%	3
Very unlikely	0.01% - 1%	2
Extremely unlikely	<0.01%	1

CONSEQUENCE RATING	
Descriptor	**Rating**
Catastrophic	5
Major	4
Significant	3
Moderate	2
Minor	1

APPENDIX 3-B: SEVERITY RISK ASSESSMENT MATRIX

				CONSEQUENCE ON TUNNELLING CYCLE				
				1	2	3	4	5
				MINOR	MODERATE	SIGNIFICANT	MAJOR	CATASTROPHIC
SCHEDULE IMPACT TO PROJECT				1 day	2 days	3 days	4 days	5 days
PROBABILITY	6	>70%	Highly likely	6	12	18	24	30
	5	50 - 70%	Likely	5	10	15	20	25
	4	15% - 50%	Occasional	4	8	12	16	20
	3	1% - 15%	Somewhat likely	3	6	9	12	15
	2	0.01% - 1%	Very unlikely	2	4	6	8	10
	1	<0.01%	Extremely unlikely	1	2	3	4	5

APPENDIX 3-C: SEVERITY INTERPRETATION TABLE

Total severity	Category	Response
18-30	Intolerable	Must eliminate or transfer risk. The risk may jeopardize the entire project, or its duration may be manifold that of the project.
12-17	Critical	Expected cost to the project is unacceptably high. This risk must be eliminated or transferred before proceeding with the project. Attempt to avoid or transfer risk.
6-11	Serious	Expected cost is high compared to total project cost. It is probably cost effective to eliminate or transfer this risk.
3-5	Acceptable	Consider eliminating or transferring. If the risk is accepted, then manage it proactively.
1-2	Negligible	The expected cost of this risk is too small to justify any mitigation effort. The risk may be accepted and ignored.

APPENDIX 4: DIRECT INFLUENCE MATRICES OF INDIVIDUAL EXPERTS

EXPERT 1

i	**1**	**2**	**3**	**4**	**5**
Schedule Risks	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
Accidents	0	3	1	0	1
Labour remonstration	2	0	2	2	0
Defective work	2	0	0	2	1
Delay in material delivery	3	1	2	0	1
Plant and machinery failure	2	1	2	3	0

EXPERT 2

	i	**1**	**2**	**3**	**4**	**5**
j	**Schedule Risks**	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
1	Accidents	0	2	1	1	1
2	Labour remonstration	1	0	2	2	2
3	Defective work	2	0	0	1	2
4	Delay in material delivery	2	2	2	0	1
5	Plant and machinery failure	2	2	1	2	0

EXPERT 3

	i	**1**	**2**	**3**	**4**	**5**
j	**Schedule Risks**	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
1	Accidents	0	3	2	1	2
2	Labour remonstration	2	0	1	2	2
3	Defective work	2	1	0	2	1
4	Delay in material delivery	3	1	2	0	2
5	Plant and machinery failure	2	1	2	2	0

EXPERT 4

	i	**1**	**2**	**3**	**4**	**5**
j	**Schedule Risks**	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
1	Accidents	0	2	2	1	2
2	Labour remonstration	2	0	2	2	2
3	Defective work	3	1	0	1	0
4	Delay in material delivery	2	2	1	0	2
5	Plant and machinery failure	3	2	2	2	0

EXPERT 5

	i	**1**	**2**	**3**	**4**	**5**
j	**Schedule Risks**	Accidents	Labour remonstration	Defective work	Delay in material delivery	Plant and machinery failure
1	Accidents	0	3	2	1	2
2	Labour remonstration	2	0	1	2	1
3	Defective work	1	1	0	1	1
4	Delay in material delivery	2	2	2	0	1
5	Plant and machinery failure	2	1	2	2	0

APPENDIX 5: MONTE CARLO SIMULATION

APPENDIX 5-A: 3 POINT ESTIMATES OF DURATION OF TUNNELLING PROCESSES FOR EACH EXPERT

EXPERT 1

I/No.	ACTIVITY	CYCLE TIME (Minutes)		
		MIN	MOST LIKELY	MAXIMUM
1	DRILLING			
1.1	Placing Jumbo	15	18	23
1.2	Drilling	130	141	148
1.3	Displace Jumbo	12	17	19
2	CHARGING			
2.1	Load Explosives	40	55	70
3	BLASTING			
3.1	Blasting	25	28	32
4	VENTILATION			
4.1	Ventilation	15	18	25
5	MUCKING			
5.1	Maneuver truck	10	14	19
5.2	Load soil	38	55	60
5.3	Transfer soil	20	28	40
5.4	Unload soil	20	25	40
6	SCALING			
6.1	Mechanical scaling	20	30	35
6.2	Manual scaling	30	45	59
7	SHOTCRETE			
7.1	Shotcrete	10	20	27
8	PRIMARY SUPPORT AND LINING			
8.1	Transfer Lining	7	12	14
8.2	Unload Lining	13	20	25
8.3	Ground support & Final lining	38	50	60
9	SURVEYING, SETTING UP etc			
9.1	Surveying and set up	15	20	30
TOTAL CYCLE TIME		**458**	**596**	**726**

EXPERT 2

I/No.	ACTIVITY	CYCLE TIME (Minutes)		
		MIN	MOST LIKELY	MAXIMUM
1	DRILLING			
1.1	Placing Jumbo	20	23	27
1.2	Drilling	125	143	160
1.3	Displace Jumbo	19	22	24
2	CHARGING			
2.1	Load Explosives	45	55	65
3	BLASTING			
3.1	Blasting	25	28	32
4	VENTILATION			
4.1	Ventilation	14	19	24
5	MUCKING			
5.1	Maneuver truck	5	12	17
5.2	Load soil	39	51	65
5.3	Transfer soil	25	33	40
5.4	Unload soil	14	27	35
6	SCALING			
6.1	Mechanical scaling	25	30	35
6.2	Manual scaling	40	48	53
7	SHOTCRETE			
7.1	Shotcrete	20	23	30
8	PRIMARY SUPPORT AND LINING			
8.1	Transfer Lining	5	8	12
8.2	Unload Lining	12	19	28
8.3	Ground support & Final lining	33	44	50
9	SURVEYING, SETTING UP etc			
9.1	Surveying and set up	10	22	30
TOTAL CYCLE TIME		**476**	**607**	**727**

EXPERT 3

I/No.	ACTIVITY	CYCLE TIME (Minutes)		
		MIN	MOST LIKELY	MAXIMUM
1	DRILLING			
1.1	Placing Jumbo	22	25	28
1.2	Drilling	140	145	150
1.3	Displace Jumbo	15	17	19
2	CHARGING			
2.1	Load Explosives	45	60	70
3	BLASTING			
3.1	Blasting	23	26	29
4	VENTILATION			
4.1	Ventilation	17	20	25
5	MUCKING			
5.1	Maneuver truck	10	14	20
5.2	Load soil	45	55	70
5.3	Transfer soil	25	35	42
5.4	Unload soil	16	28	32
6	SCALING			
6.1	Mechanical scaling	30	33	40
6.2	Manual scaling	45	47	53
7	SHOTCRETE			
7.1	Shotcrete	18	20	25
8	PRIMARY SUPPORT AND LINING			
8.1	Transfer Lining	8	10	14
8.2	Unload Lining	15	17	22
8.3	Ground support & Final lining	34	46	55
9	SURVEYING, SETTING UP etc			
9.1	Surveying and set up	15	20	25
TOTAL CYCLE TIME		**523**	**618**	**719**

EXPERT 4

I/No.	ACTIVITY	CYCLE TIME (Minutes)		
		MIN	MOST LIKELY	MAXIMUM
1	DRILLING			
1.1	Placing Jumbo	15	22	27
1.2	Drilling	130	140	157
1.3	Displace Jumbo	20	22	24
2	CHARGING			
2.1	Load Explosives	38	55	65
3	BLASTING			
3.1	Blasting	20	23	25
4	VENTILATION			
4.1	Ventilation	17	20	23
5	MUCKING			
5.1	Maneuver truck	15	14	18
5.2	Load soil	36	54	60
5.3	Transfer soil	25	30	35
5.4	Unload soil	18	25	30
6	SCALING			
6.1	Mechanical scaling	25	29	33
6.2	Manual scaling	40	45	55
7	SHOTCRETE			
7.1	Shotcrete	13	25	32
8	PRIMARY SUPPORT AND LINING			
8.1	Transfer Lining	8	10	16
8.2	Unload Lining	15	18	25
8.3	Ground support & Final lining	40	43	50
9	SURVEYING, SETTING UP etc			
9.1	Surveying and set up	14	20	35
TOTAL CYCLE TIME		**489**	**595**	**710**

EXERT 5

I/No.	ACTIVITY	CYCLE TIME (Minutes)		
		MIN	MOST LIKELY	MAXIMUM
1	DRILLING			
1.1	Placing Jumbo	23	27	30
1.2	Drilling	125	146	160
1.3	Displace Jumbo	9	12	14
2	CHARGING			
2.1	Load Explosives	47	60	75
3	BLASTING			
3.1	Blasting	27	30	32
4	VENTILATION			
4.1	Ventilation	12	18	23
5	MUCKING			
5.1	Maneuver truck	10	16	21
5.2	Load soil	42	60	70
5.3	Transfer soil	30	39	43
5.4	Unload soil	22	30	38
6	SCALING			
6.1	Mechanical scaling	25	28	32
6.2	Manual scaling	45	50	55
7	SHOTCRETE			
7.1	Shotcrete	14	27	36
8	PRIMARY SUPPORT AND LINING			
8.1	Transfer Lining	7	10	14
8.2	Unload Lining	10	21	25
8.3	Ground support & Final lining	30	42	55
9	SURVEYING, SETTING UP etc			
9.1	Surveying and set up	11	23	30
TOTAL CYCLE TIME		**489**	**639**	**753**

APPENDIX 5-B: 3 POINT ESTIMATES OF IMPACTS OF TUNNELLING RISK ON DURATION FOR EACH EXPERT

EXPERT 1

R/No	RISK	IMPACT ON DURATION		
		MIN	MOST LIKELY	MAX
R1	Machine Breakdown	0	50	450
R2	Accident	8	15	20
R3	Labour remonstration	180	420	960
R4	Delay in Material Delivery	15	30	60
R5	Defective Work	30	45	60

EXPERT 2

R/No	RISK	IMPACT ON DURATION		
		MIN	MOST LIKELY	MAX
R1	Machine Breakdown	0	65	540
R2	Accident	13	20	25
R3	Labour remonstration	180	540	960
R4	Delay in Material Delivery	10	30	50
R5	Defective Work	40	50	54

EXPERT 3

R/No	RISK	IMPACT ON DURATION		
		MIN	MOST LIKELY	MAX
R1	Machine Breakdown	0	60	480
R2	Accident	10	15	20
R3	Labour remonstration	180	480	900
R4	Delay in Material Delivery	15	30	35
R5	Defective Work	15	30	50

EXPERT 4

R/No	RISK	IMPACT ON DURATION		
		MIN	MOST LIKELY	MAX
R1	Machine Breakdown	0	55	480
R2	Accident	10	13	20
R3	Labour remonstration	300	460	1020
R4	Delay in Material Delivery	5	18	25
R5	Defective Work	40	45	50

EXPERT 5

R/No	RISK	IMPACT ON DURATION		
		MIN	MOST LIKELY	MAX
R1	Machine Breakdown	0	70	450
R2	Accident	9	12	15
R3	Labour remonstration	360	500	960
R4	Delay in Material Delivery	5	17	30
R5	Defective Work	50	55	56

APPENDIX 5-C: RISK INPUT DATA FOR MCS AND DES

1. ACCIDENTS			
Risk	Probabilities	From alpha cut T-Matrix in DEMATEL	MODEL INPUT
Accidents	10%	1.4188969	14%
Labour remonstration	10%	1.4084005	14%
Defective work	10%	1.3721066	14%
Delay in material delivery	10%	0	0%
Plant and machinery failure	10%	0	0%
Risk			
Accidents	20%	1.4188969	28%
Labour remonstration	20%	1.4084005	28%
Defective work	20%	1.3721066	27%
Delay in material delivery	20%	0	0%
Plant and machinery failure	20%	0	0%
Risk			
Accidents	30%	1.4188969	43%
Labour remonstration	30%	1.4084005	42%
Defective work	30%	1.3721066	41%
Delay in material delivery	30%	0	0%
Plant and machinery failure	30%	0	0%
Risk			
Accidents	40%	1.4188969	57%
Labour remonstration	40%	1.4084005	56%
Defective work	40%	1.3721066	55%
Delay in material delivery	40%	0	0%
Plant and machinery failure	40%	0	0%
Risk			
Accidents	50%	1.4188969	71%
Labour remonstration	50%	1.4084005	70%
Defective work	50%	1.3721066	69%
Delay in material delivery	50%	0	0%
Plant and machinery failure	50%	0	0%
Risk			

1. ACCIDENTS			
Risk	Probabilities	From alpha cut T-Matrix in DEMATEL	MODEL INPUT
Accidents	60%	1.4188969	85%
Labour remonstration	60%	1.4084005	85%
Defective work	60%	1.3721066	82%
Delay in material delivery	60%	0	0%
Plant and machinery failure	60%	0	0%

2. LABOUR REMONSTRATION			
Risk	Probabilities	From alpha cut T-Matrix in DEMATEL	MODEL INPUT
Accidents	10%	1.6558952	17%
Labour remonstration	10%	0	0%
Defective work	10%	1.407775	14%
Delay in material delivery	10%	1.3500852	14%
Plant and machinery failure	10%	0	0%
Risk			
Accidents	20%	1.6558952	33%
Labour remonstration	20%	0	0%
Defective work	20%	1.407775	28%
Delay in material delivery	20%	1.3500852	27%
Plant and machinery failure	20%	0	0%
Risk			
Accidents	30%	1.6558952	50%
Labour remonstration	30%	0	0%
Defective work	30%	1.407775	42%
Delay in material delivery	30%	1.3500852	41%
Plant and machinery failure	30%	0	0%
Risk			
Accidents	40%	1.6558952	66%
Labour remonstration	40%	0	0%
Defective work	40%	1.407775	56%
Delay in material delivery	40%	1.3500852	54%
Plant and machinery failure	40%	0	0%
Risk			
Accidents	50%	1.6558952	83%
Labour remonstration	50%	0	0%
Defective work	50%	1.407775	70%
Delay in material delivery	50%	1.3500852	68%
Plant and machinery failure	50%	0	0%
Risk			
Accidents	60%	1.6558952	99%
Labour remonstration	60%	0	0%

2. LABOUR REMONSTRATION			
Risk	Probabilities	From alpha cut T-Matrix in DEMATEL	MODEL INPUT
Defective work	60%	1.407775	84%
Delay in material delivery	60%	1.3500852	81%
Plant and machinery failure	60%	0	0%

3. DEFECTIVE WORK			
Risk	Probabilities	From alpha cut T-Matrix in DEMATEL	MODEL INPUT
Accidents	10%	1.3336691	13%
Labour remonstration	10%	0	0%
Defective work	10%	0	0%
Delay in material delivery	10%	0	0%
Plant and machinery failure	10%	0	0%
Risk			
Accidents	20%	1.3336691	27%
Labour remonstration	20%	0	0%
Defective work	20%	0	0%
Delay in material delivery	20%	0	0%
Plant and machinery failure	20%	0	0%
Risk			
Accidents	30%	1.3336691	40%
Labour remonstration	30%	0	0%
Defective work	30%	0	0%
Delay in material delivery	30%	0	0%
Plant and machinery failure	30%	0	0%
Risk			
Accidents	40%	1.3336691	53%
Labour remonstration	40%	0	0%
Defective work	40%	0	0%
Delay in material delivery	40%	0	0%
Plant and machinery failure	40%	0	0%
Risk			
Accidents	50%	1.3336691	67%
Labour remonstration	50%	0	0%
Defective work	50%	0	0%
Delay in material delivery	50%	0	0%
Plant and machinery failure	50%	0	0%
Risk			
Accidents	60%	1.3336691	80%
Labour remonstration	60%	0	0%

3. DEFECTIVE WORK			
Risk	Probabilities	From alpha cut T-Matrix in DEMATEL	MODEL INPUT
Defective work	60%	0	0%
Delay in material delivery	60%	0	0%
Plant and machinery failure	60%	0	0%

4. DELAY IN MATERIAL DELIVERY			
Risk	Probabilities	From alpha cut T-Matrix in DEMATEL	MODEL INPUT
Accidents	10%	1.7658663	18%
Labour remonstration	10%	1.4062138	14%
Defective work	10%	1.4754383	15%
Delay in material delivery	10%	0	0%
Plant and machinery failure	10%	0	0%
Risk			
Accidents	20%	1.7658663	35%
Labour remonstration	20%	1.4062138	28%
Defective work	20%	1.4754383	30%
Delay in material delivery	20%	0	0%
Plant and machinery failure	20%	0	0%
Risk			
Accidents	30%	1.7658663	53%
Labour remonstration	30%	1.4062138	42%
Defective work	30%	1.4754383	44%
Delay in material delivery	30%	0	0%
Plant and machinery failure	30%	0	0%
Risk			
Accidents	40%	1.7658663	71%
Labour remonstration	40%	1.4062138	56%
Defective work	40%	1.4754383	59%
Delay in material delivery	40%	0	0%
Plant and machinery failure	40%	0	0%
Risk			
Accidents	50%	1.7658663	88%
Labour remonstration	50%	1.4062138	70%
Defective work	50%	1.4754383	74%
Delay in material delivery	50%	0	0%
Plant and machinery failure	50%	0	0%
Risk			
Accidents	60%	1.7658663	106%
Labour remonstration	60%	1.4062138	84%

4. DELAY IN MATERIAL DELIVERY			
Risk	Probabilities	From alpha cut T-Matrix in DEMATEL	MODEL INPUT
Defective work	60%	1.4754383	89%
Delay in material delivery	60%	0	0%
Plant and machinery failure	60%	0	0%

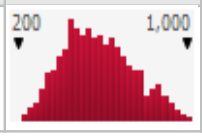
5. PLANT AND MACHINERY FAILURE			
Risk	Probabilities	From alpha cut T-Matrix in DEMATEL	MODEL INPUT
Accidents	10%	1.832262	18%
Labour remonstration	10%	1.4514518	15%
Defective work	10%	1.5447995	15%
Delay in material delivery	10%	1.4754377	15%
Plant and machinery failure	10%	0	0%
Risk			
Accidents	20%	1.832262	37%
Labour remonstration	20%	1.4514518	29%
Defective work	20%	1.5447995	31%
Delay in material delivery	20%	1.4754377	30%
Plant and machinery failure	20%	0	0%
Risk			
Accidents	30%	1.832262	55%
Labour remonstration	30%	1.4514518	44%
Defective work	30%	1.5447995	46%
Delay in material delivery	30%	1.4754377	44%
Plant and machinery failure	30%	0	0%
Risk			
Accidents	40%	1.832262	73%
Labour remonstration	40%	1.4514518	58%
Defective work	40%	1.5447995	62%
Delay in material delivery	40%	1.4754377	59%
Plant and machinery failure	40%	0	0%
Risk			
Accidents	50%	1.832262	92%
Labour remonstration	50%	1.4514518	73%
Defective work	50%	1.5447995	77%
Delay in material delivery	50%	1.4754377	74%
Plant and machinery failure	50%	0	0%
Risk			
Accidents	60%	1.832262	110%
Labour remonstration	60%	1.4514518	87%

5. PLANT AND MACHINERY FAILURE			
Risk	Probabilities	From alpha cut T-Matrix in DEMATEL	MODEL INPUT
Defective work	60%	1.5447995	93%
Delay in material delivery	60%	1.4754377	89%
Plant and machinery failure	60%	0	0%

APPENDIX 5-D: SAMPLE OUT PUT REPORT FOR MCS

@RISK Output Results

Performed By: Joy
Date: Wednesday, May 15, 2019 10:26:11 AM

Name	Worksheet	Cell	Graph	Min	Mean	Max	5%	95%	Errors
Minutes added to plan	Risk Register	L9		249	585	997	354	856	0

APPENDIX 6: SAMPLE OUT PUT REPORT FOR DES

2:42:22PM **Category Overview** May 1, 2019

Values Across All Replications

Drill and Blast Tunnelling ARENA Simulation

Replications: 20 Time Units: Minutes

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
cycle	903.75	140.33	630.56	1524.88	630.56	1524.88

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
cycle	0.00	0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
cycle	0.00	0.00	0.00	0.00	0.00	0.00

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
cycle	0.00	0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
cycle	0.00	0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
cycle	903.75	140.33	630.56	1524.88	630.56	1524.88

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
cycle	1.0000	0.00	1.0000	1.0000

Number Out	Average	Half Width	Minimum Average	Maximum Average
cycle	1.0000	0.00	1.0000	1.0000

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
cycle	0.0941	0.01	0.06568342	0.1588	0.00	1.0000

Model Filename: D:\CLASSWORK\Thesis\Tunnelling model\Final_Model_Rev_1 Page 2 of 8

APPENDIX 7: TUNNELLING DATA COLLECTED FROM DOCUMENT REVIEW

Description.	Tunnel length (m)	Advance rate (m/cycle)	Number of cycles	Actual duration (As-Built)			Duration (minutes)	Cycle duration (minutes)
				Start (excavation)	Completion (Lining)	Duration (days)		
Tunnel No.3	347	5	69.400	12/20/2015	9/22/2016	264.000	126720.000	1825.937
Tunnel No.4	1536	5	307.200	6/2/2015	2/2/2017	589.000	282720.000	920.313
Tunnel No.5	403	5	80.600	2/22/2016	11/17/2016	232.000	111360.000	1381.638
Tunnel No.6	326	5	65.200	5/4/2016	12/22/2016	226.000	108480.000	1663.804
Tunnel No.7	287	5	57.400	11/23/2015	6/26/2016	287.000	137760.000	2400.000