A BAYESIAN BELIEF NETWORK BASED DELAY RISK ASSESSMENT TOOL FOR TUNNEL PROJECTS – BBN TUNNEL

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GÜLSÜM ÇAĞIL KÖSEOĞLU BALTA

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ABSTRACT

A BAYESIAN BELIEF NETWORK BASED DELAY RISK ASSESSMENT TOOL FOR TUNNEL PROJECTS – BBN TUNNEL

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Tunnel constructions are characterized by high degrees of uncertainty, due to two major factors; -geologic conditions, which can seldom be exactly known and -uncertainties in construction process itself as it highly depends on the performance of the equipment and workmanship. Therefore, due to the specific properties of tunnel construction projects, there is an increasing urgency to assess and manage the risks systematically. Initially, an extensive literature review was carried out to identify risks and proposed methods for risk identification in tunneling projects. Then, to gain insight into the practice of risk assessment of tunneling projects within the industry, current practices in a construction company are investigated and research needs are determined. In the light of these findings, major aims of the thesis are identified as; construction of a risk taxonomy that links risk with delay, development of a methodology for risk assessment and a tool that can be used to identify risk mitigation strategies to minimize delay. In collaboration with a construction company, first, major risk events, vulnerability and risk factors were determined, and a taxonomy was developed. Then, a dependency based probabilistic risk analysis method based on Bayesian Belief Networks (BBNs) was proposed. BBN model was developed and validated by utilizing several expert knowledge elicitation techniques. Finally, a decision support tool, BBN Tunnel, that can predict delay and estimate the cost-time impact of utilizing different strategies was developed. BBN Tunnel was tested, validated and its utilization in a real project was demonstrated by a case study. Results demonstrate that the methodology and tool may be used to integrate several risk factors, draw a comprehensive risk map, predict delay and help decision-makers to formulate risk management strategies to mitigate delay.

Keywords: Risk Assessment, Bayesian Belief Network, Tunnel Projects

ÖZ

TÜNEL PROJELERİ İÇİN BAYES AĞI TABANLI BİR GECİKME RİSKİ DEĞERLENDİRME ARACI – BBN TUNNEL

Köseoğlu Balta, Gülsüm Çağıl
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Tünel inşaatları temel olarak iki ana nedenden dolayı yüksek belirsizliğe sahip olup, bunlar tam ve kesin olarak belirlenemeyen zemin koşulları ve inşa yönteminin makine ve işçilik performansına büyük ölçüde bağlı olması nedeniyle yöntemin kendinden kaynaklanan belirsizlikler olarak tanımlanmaktadır. Bu nedenle, tünel projelerinin doğrusal ve kendine özgü özellikleri nedeniyle bu tür projelerdeki risklerin sistematik olarak değerlendirilip yönetilmesi büyük önem taşımaktadır. İlk olarak, tünel projelerindeki risklerin belirlenmesi ve risk belirleme yöntemleri hakkında kapsamlı bir literatür araştırması yapılmıştır. Daha sonra, sektörde uygulanmakta olan risk değerlendirme yöntemleri hakkında bilgi sahibi olabilmek amacıyla, bir inşaat firmasındaki uygulamalar incelenmiş ve araştırma gereksinimleri belirlenmiştir. Bu kapsamda, tezin temel amaçları; gecikme ile bağlantılı bir risk taksonomisinin oluşturulması, bir risk değerlendirme metodu ve gecikmeyi minimize edecek risk azaltma stratejilerinin belirlenebileceği bir aracının geliştirilmesi olarak belirlenmiştir. Bir inşaat firmasının görüşleri doğrultusunda, önce temel risk olayları, hassasiyet ve risk faktörleri belirlenmiş ve taksonomi oluşturulmuştur. Daha sonra, Bayes İnanç Ağı (BİA) tabanlı bağımlılık bazlı olasılıksal bir risk analiz modeli öngörülmüştür. BİA modeli, birçok uzman bilgi edinme yöntemi kullanılarak oluşturulmuş ve doğrulanmıştır. Son olarak, gecikme süresini ve farklı stratejilerin maliyet-süre etkilerini tahmin edebilen bir karar destek aracı, BBN Tunnel, oluşturulmuştur. BBN Tunnel, test edilmiş, doğrulanmış ve örnek bir çalışma ile gerçek bir proje üzerinde uygulanmıştır. Bu çalışmalar neticesinde, geliştirilen metot ve aracın çeşitli risk faktörlerini entegre etmek, kapsamlı bir risk haritası çizmek, gecikmeyi tahmin etmek ve karar vericilerin gecikme riskini azaltmaya yönelik risk yönetme stratejileri oluşturmalarına yardımcı olmak amaçlarıyla kullanılabileceğini göstermiştir.

Anahtar Kelimeler: Risk Değerlendirme, Bayes İnanç Ağı, Tünel Projeleri

To my beloved family,

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LIST OF ABBREVIATIONS

ABBREVIATIONS	
ACF	Assumptions Testing and Control Factors
AHP	Analytical Hierarchy Process
APM	Association for Project Management
BBN	Bayesian Belief Network
BN	Bayesian Network
CPT	Conditional Probability Table
DAG	Directed Acyclic Graph
DS	Decision Support
DTA	Decision Tree Analysis
EKE	Expert Knowledge Elicitation
E&M	Electro-Mechanical
EPB	Earth Pressure Balance
EPBM	Earth Pressure Balance Tunnel Boring Machine
ETA	Event Tree Analysis
FAHP	Fuzzy Analytical Hierarchy Process
FBN	Fuzzy Bayesian Network
FT	Fault Tree
FTA	Fault Tree Analysis
GIS	Geographic Information System

GDP	Gross Domestic Product
HAZOP	Hazard and Operability Analysis
IDEF	Integrated DEFinition
IRM	Integrated Risk Management
ISO	International Organization for Standardization
ITA	International Tunneling Association
KA	Knowledge Acquisition
NATM	New Austrian Tunneling Method
NGT	Nominal Group Technique
OECD	The Organization for Economic Co-operation and Development
PHA	Preliminary Hazard Analysis
PRA	Project Risk Assessment
PRM	Project Risk Management
PMI	Project Management Institute
PMBoK	Project Management Body of Knowledge
RMP	Risk Mapping Procedure
SAMIAM	Sensitivity Analysis, Modeling, Inference and More
TBM	Tunnel Boring Machine
NATM	New Austrian Tunneling Method
UCLA	University of California
UK	United Kingdom
USA	United States of America

CHAPTER 1

INTRODUCTION

This chapter of the thesis introduces the research background on project risk assessment literature, Bayesian Belief Networks in risk assessment research, problem statement for tunnel projects, aims and objectives of the research, proposed contributions and the structure of the dissertation.

1.1. BACKGROUND OF THE STUDY

Risk is generally described as an uncertain event/condition which has a positive or negative result on project objectives (PMI, 2013). Risks bring about rewards or threats to the project success and management of these risks (i.e. risk management) aim to increase the effects of positive events and reduce impacts of negative events.

According to PMI (2013), risk management is one of the ten functions of project management. It consists of planning, identifying, analysis, responding, monitoring and controlling project risks. An effective risk management process not only allows examining alternatives and controlling/reducing threats that leads to delays, costs and disputes, but also ensures being prepared for treatment of risks, improving project performances and increasing the chances of success through directing the decision makers towards predetermined objectives. According to Guofeng et al. (2011), the process becomes more demanding for construction projects due to the amount of time, high construction costs and the complex network of parties involved in such projects.

ISO (2009) refers to risk assessment as the combination of; identification, analysis and evaluation steps in the overall risk management procedure. Williams (1995) argues that the assessment stage is crucial in order to accomplish project success and decision-making and Skorupka (2008) supports the idea that without successful application of risk identification and assessment processes, the other stages of risk management cannot be effective. Therefore, for construction projects as well, risk assessment should constitute the first and the most important stage of the risk management procedure.

The first methods utilized for risk assessment included probabilistic methods and Monte Carlo simulation. In 1980's probability-impact matrices were used for risk analysis. Ashley and Bonner (1987) utilized influence diagrams to determine the effects of political risks on project cost and earnings for international construction projects. At the end of the same decade, fuzzy theory was introduced to the construction risk assessment field (Taroun, 2014). In the 90's the analytical hierarchy process (AHP) and again influence diagramming were used in the construction industry which were later utilized for developing decision support systems in risk assessment processes (Taroun, 2014). However, these risk assessment methods that have been conducted so far were lack of analyzing the dependencies between governing risk factors. In order to overcome this obstacle, Bayesian belief network (BBN) was one of the first methods that have been proposed in the literature to model the relations between risks in the construction industry (Taroun, 2014).

The BBNs most basically use conditional probabilities to define the causal relations between the variables in a problem domain. The most distinct property of BBNs in risk assessment is that they provide the advantage of combining probabilistic information and interrelations between variables. The attractiveness of using BBNs in the analysis of uncertainties has increased around 1995 (Fan and Yu, 2004). According to Weber et al. (2012), use of BBNs in risk analysis perspective increased especially since 2001. One of the first contributions were made by Hudson et al. (2002) and Qien (as cited in Weber et al., 2012) integrating multiple aspects of the problem that is being analyzed. The major strengths of BBNs in risk analysis has been reported by Weber et al. (2012) as;

- Ability to represent complicated systems with multiple interdependencies,
- Ability to quantify relations between low probability and high probability events contributing to the overall outcome,
- Providing combination of real case data and expert knowledge,
- Ability to perform problem diagnosis and feedback analysis for risk assessment and mitigation purposes.

In the construction industry, utilization of the BBN method focused initially on determining operational efficiencies, system diagnosis, productivity estimation, cost estimation and probabilistic risk analysis (Luu et al., 2009).

In this research, the objective is identified as determining schedule risks in tunnel projects and to develop a BBN based decision support tool for predicting project delays. The reason behind focusing on tunnel constructions, utilizing the BBN method and the process behind development of the tool is provided in the following sections of this thesis.

1.2. PROBLEM STATEMENT

Tunnel construction has been increasingly accelerating throughout the world. They constitute one of the many aspects of transportation infrastructure projects, that make 0.4-1.6% of the world's GDP (OECD, 2019). Due to the high costs and publicities involved in tunnel projects like highway tunnels or railway tunnels, these projects possess an important part in the infrastructure investments.

Underground infrastructure works (i.e. tunneling) is characterized by high degrees of uncertainty, due to two major factors; geologic conditions, which are seldom known for certain, uncertainties involved in the construction process itself as it highly depends on the performance of equipment and workmanship. To specify, these projects include high risks on all parties due to the inherent uncertainties, varying ground conditions along the tunnel length, importance of design details for critical damage/collapse of the tunnel, high investment costs, combination of many factors for tunnel safety and complex mechanical operations that are utilized during the tunnel boring process. As a result, there have been many incidents in various tunneling projects, that have resulted with delays, cost overruns, or injuries and loss of life. According to Artopoulos (2015), in the period between 1994-2015 twenty-six tunnel projects faced collapse or losses due to flood or fire, based on design or workmanship errors. The total amount of costs associated with these failures reach 621 million USD. As these projects use large amounts of resources and have been widely publicized, society pressure is usually high when facing these problems.

Tunnel projects involve many different sources of risks in terms of both estimated costs and project durations. Various researches have been conducted for risk analysis of tunnel constructions however, majority of existing risk analysis systems deal only with the effects of certain geological, construction uncertainties and tunnel safety issues. On the other hand, there are other sources of risks which have not been considered in, that can have substantial consequences on the tunnel processes.

In addition to the limitations in scope of identification of risks, there are certain drawbacks in applying risk assessment methods as well. In Sturk et al. (1996)'s study, it is noted that the majority of the risk assessment methods involve either deterministic approaches or intuitive analysis of specific problems. However, according to Eskesen et al. (2004), effective risk management processes can be accomplished by clear definition of objectives, risk mitigation actions and involvement of various project participants. Therefore, there is an increasing urgency to comprehensively assess and manage the risks associated with tunnel construction projects.

For the large-scale projects such as tunnel constructions the project success is usually measured by schedule performance. According to Han et al. (2009), time overrun is the major dominating concern of project performance which also highly effects cost overruns and disputes. Therefore, controlling delay risks in tunnel constructions also provides means to minimize cost risks. Konstantis et al. (2016) examined various tunnel projects and found out that the time overruns in tunnel constructions range from 1 month up to 4 years with an average of approximately 18 months. Siang et al. (2017) and Konstantis et al. (2016) also suggested that time overruns typically impact cost increases. Thus, schedule risk analysis in tunnel projects provide the key measure for a feasible risk assessment.

As a result, based on the limitations of current risk assessment methods briefly given here and due to reliance on schedules for success in tunnel projects; this thesis is focused on developing a methodology that is able to incorporate accumulated past data, consider relations between various risk sources, determine feasible risk mitigation strategies and provide a decision support mechanism for tunnel projects to maintain an efficient delay risk assessment process. While BBNs have been chosen to create the probabilistic delay risk assessment model, to accomplish the decision support perspective a tool is created.

1.3. AIMS AND OBJECTIVES OF THE RESEARCH

The main objective of this research is to provide a novel project risk assessment methodology for tunnel projects based on an empirically validated computational model. The model is expected to reflect the characteristics of TBM type of tunnel projects and provide a comprehensive framework that can handle external and internal project risks involved for contractors, that can be used in different project stages until the construction is completed. Due to the advantage of combining expert data and probabilistic analysis, BBNs have been chosen as the basis to carry out the delay risk assessment methodology. To automate the risk analysis calculations and provide a decision support mechanism, a risk assessment tool is created based on case study research and company specific data. Combined together, delay risks in tunnel projects will be assessed and risk mitigation strategies will be evaluated by TBM tunnel professionals.

In light of these, the objectives of this thesis are identified as;

- To conduct case study research in national and international tunnel construction projects, understand the problems faced in real tunnel projects and identify the risk involved.
- To develop a generic risk taxonomy for tunnel projects that links with delay. This risk taxonomy will contain information regarding categories, sources, potential causes, consequences of schedule risks. The taxonomy will be made available to contractors and experts in the tunneling field and aims to provide the most comprehensive tunneling risk data available.
- To develop a Bayesian network of risk-related factors that impact delay which will lead to a better understanding of the main causes, consequences and relations between the risk factors.
- To develop a risk assessment methodology specific for TBM tunnel constructions using BBN, that includes various project parties contributing to delays in tunnel projects.
- To demonstrate how strategies can be formulated to decrease/eliminate resultant delay risks in tunnel projects.
- To create a decision support tool for tunnel projects practitioners for delay risk assessment and risk handling purposes.

1.4. CONTRIBUTION

This research will provide a comprehensive risk assessment method with a decision support tool to predict delays and formulate strategies to minimize delay for tunnel projects. The developed methodology will systematically analyze the risks, their dependencies, their contribution to time overrun (delay) and impacts on project budget if different strategies are used to mitigate them. In order to do this, a risk taxonomy is developed, a delay prediction model is created by utilizing BBN method and finally, a tool is built that will aid evaluating alternative risk mitigation strategies to decrease project delay in tunnel projects.

The explained method is developed through experience and real case projects of a construction company and is tested through actual project data. This experience is aimed to provide an insight for other companies in the field, as it will improve the current intuitive processes. The methodology will enable the tunnel contractors to identify the relevant risks involved in each project, estimate their impacts on project delays, formulate and examine different strategies together with their cost outcomes. As stated by Eskesen et al. (2004) the risk management approaches in tunnel projects can be effective if the risk management team "*have the whole risk management process in their minds when carrying out their work*".

1.5. DISPOSITION

This research is composed of six consecutive sections to develop the delay risk assessment decision support tool; 1) research design, 2) developing a risk-delay taxonomy, 3) developing the computational delay assessment model, 4) developing the decision support tool, 5) validation of the tool, 6) implementation of the methodology on a real tunnel project.

In Chapter 2, research background is summarized on tunnel constructions and project risk assessment methods. After briefly introducing the technical background of tunnel works, the risk assessment literature on tunnel projects are provided and research on delay risks is concisely summarized. Next, literature on project risk assessment and management is given. Special emphasis is given on reviewing risk management concepts, brief description of Bayesian theory and use of BBNs in the section on project risk assessment.

Chapter 3 constitutes the foundation of this research, which aims to explain the research objectives and the methodology adopted in this thesis. The research development process in this thesis has been carried out in collaboration with a construction company. Therefore, this chapter starts with the brief introduction to the company and the case study research methods. Then, case study projects of the company are summarized and discussions on limitations in current tunnel risk assessment methods are depicted. Research objectives are defined to overcome the identified limitations. Based on these and the works of Luu et al. (2009) and Cardenas et al. (2014), a research design is developed. In the final section of this chapter, the methodology of the research is described based on the research objectives identified and the methods that are used throughout the thesis.

In Chapter 4, the risk taxonomy that is created to provide a comprehensive database for risks involved in tunnel projects is introduced. Findings from the literature, empirical research, and experts are given.

Chapter 5 presents the development of the BBN based delay risk assessment model. In this phase of the research, experts are consulted most intermittently. Therefore, theoretical background on expert knowledge elicitation is given in the beginning of this chapter. Following the theoretical background, the expert elicitation sessions carried out during this phase are summarized. The model development process is explained through mapping of the BBN model and numerical probability assignments of tunnel construction risks through these elicitation sessions. In the final section, the created model is subjected to sensitivity and assumptions testing procedures.

After these tests are finalized, the decision support tool is developed as explained in Chapter 6. In order to do that, strategies are defined for risk mitigating purposes. Then using the results of sensitivity analysis and identified risk mitigation strategies, the decision support tool with a unique user interface is developed to automate the risk assessment method. This tool contained the risk assessment and strategy assessment aspects and named as BBN Tunnel. In order to accomplish these steps, numerous expert elicitation sessions have been conducted.

After the BBN Tunnel tool is presented, validation of the developed methodology is explained in Chapter 7. The chapter starts by providing a brief theoretical background on validation methods emphasizing the BBNs. Then a suitable validation methodology is developed and explained in order to meet the requirements of this research. It consists of validating the BBN model as well as the decision support tool. The final section of the chapter summarizes the findings of these numerous validation tests.

In Chapter 8 the final phase of the research is described. It involves implementation of BBN Tunnel tool to a completed real case study tunnel project. Similar to the previous research phases, expert elicitation methods have been used and discussions on implementation results that are carried out with two different experts taking part in the same case study project have been presented.

In the final chapter, Chapter 9, the research findings are summarized with emphasis on the most important outputs pinpointing the novelty of the methodology that is developed in this thesis. Major findings of the research, its contributions to the theory, expected benefits for practice and recommendations for further studies are stated.

CHAPTER 2

RESEARCH BACKGROUND

2.1. INTRODUCTION

The process of construction projects in general is complicated and involves many parties. In case of tunnel constructions, the degree of uncertainty increases more as these projects also involve additional ambiguities due to geological conditions, performance of technical equipment and specialized workmanships. This chapter overviews the theoretical background of tunnel projects and project risk assessment and risk management subjects. To do this, first a brief history of tunnel constructions is given, emphasizing railway tunnels. Then technical summary of construction methods applied in tunnel constructing is introduced by stressing out TBMs and previous studies on tunnel risk assessment are briefly reviewed. After that, risk assessment and risk management concepts are described in this chapter. Then, the Bayesian theory is introduced to provide background for the forthcoming research with also announcing the widely used Bayesian Belief Network (BBN) method developed by Pearl (1982). In the final section, applications of BBN for project risk assessment are reviewed.

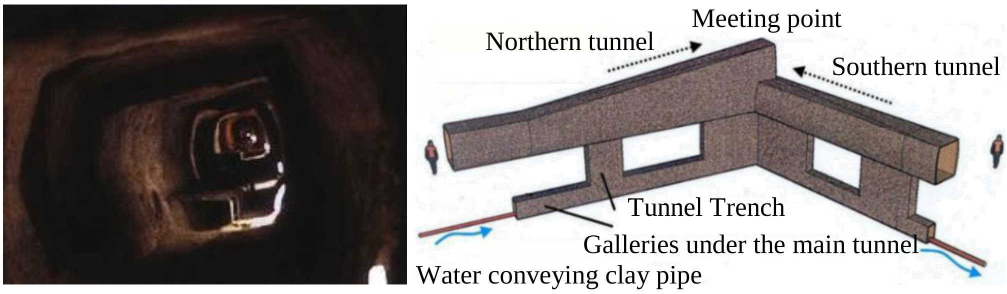
2.2. TUNNEL PROJECTS

2.2.1. History and Evolution of Tunnel Constructions

Tunnel construction was originated from the need of passing over natural barriers such as mountains or sources of water. In modern times, the main uses of tunnels are mainly for railway, road or pedestrian transportation, navigation, and conveyance for water supply, sewerage, hydroelectric power plants and routing power cables (Garry, 2012).

According to Garry (2012), the earliest underwater tunnel was built by the Babylonians at 2180 B.C. with the "cut and cover" method under the Euphrates River for diversion of its bed. Even though it is detailed in Section 2.2.3, cut-and-cover generally is referred as a tunneling method which starts by excavation of a trench, followed by constructing the tunnel structure and finalized by covering the tunnel roof (or left open according to purpose) (Pamukçu, 2015).

The ancient Greeks and the Romans built several tunnels for carrying water and mining. The tunnel of Samos on the Greek Island of Samos excavated in 6th century B.C., is regarded as one of the greatest engineering achievements of early times. The 1036 m long tunnel was excavated through solid limestone using picks, hammers and chisels for water conveying purposes (Apostol, 2004).



(a) (b)

Figure 2.1. The Tunnel of Samos (a) Cross Section of the tunnel (Apostol, 2004); (b) A sketch of meeting points of the tunnel boring sections (Angistalis and Kouroumli, 2014)

After the use of gunpowder, conventional methods in tunneling such as shovels and picks have been replaced by blasting. At a more recent history in Europe, the first of several major canal tunnels was built in France. Canal du Midi, also known as Canal Royal de Languedoc, was part of the first canal linking the Atlantic Ocean and the Mediterranean Sea, built in 1666-81 with a length of 157 meters and a cross section of 6.7 by 8.2 meters (Chapman et al., 2010). In United Kingdom, development of the canal systems during the industrial revolution in the 18th century gave examples of one of the first tunnels with considerable lengths; the Grand Trunk Canal (1777), Standedge Tunnel (1811) and Harecastle Tunnel (1827) (Stack, 1982). In the 18th and early 19th centuries many other canal tunnels were built in Europe and United States (Kolymbas, 2008).

Tunneling shield method was one of the breakthroughs in the field, which was introduced by Sir Marc Isambard Brunel to excavate a tunnel beneath the River Thames in London in 1825 (Garry, 2012). The method involves construction of a cast iron shield, also known as Brunel's Shield, to support the tunnel face and protect the miners.

The workers still did the excavation work, threw the spoil on a moving platform and erect the brickwork lining the tunnel. The section of the tunnel was rectangular, and the lining was constructed with bricks (Figure 2.2). Unfortunately, the tunnel construction had to be stopped due to various disrupting incidents caused by soil conditions and was finally finished in 1842 (Chapman et al., 2010).

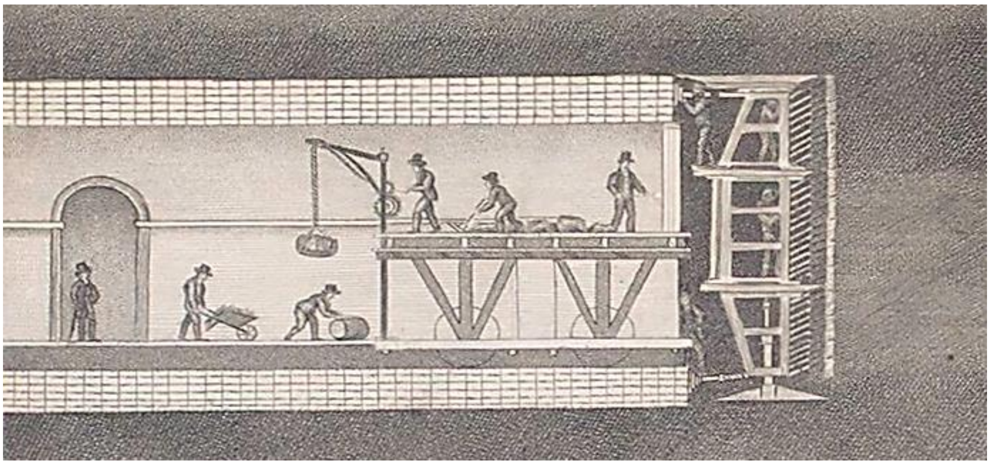


Figure 2.2 Longitudinal Section of the Thames Tunnel (Thames Tunnel Corporation, 1836; Credit: New York Public Library)

2.2.2. Evolution of Railway Tunnels

The growth of the mining activities since the 19th century had also an accelerating effect on tunnel engineering which triggered new developments. Conventional tunneling worldwide was dominated by timber until this period, then it was gradually replaced by steel and combination of timber and steel as support systems. Starting from 1830 with the introduction of railway constructions, tunneling increased in the UK immensely (Chapman et al., 2010). During the period of 1830-1890 it further advanced with the creation of TBMs that will be summarized in Section 2.2.3.4. During this period, tunnel constructions in UK reached 50 with railway transportation projects.

In the second half of the 20th century and early 21st century, due to increased urban populations, there was a higher demand for distribution of underground railway tunnels in the urban transportation network. Longo (2006) claims that the main reasons for the increase of underground transportation can be listed as;

- public pressure for a better quality of life in the cities,
- technological advances,
- increasing cost of surface area in the cities and the impact of construction at the surface.

These lead to the construction of various novel tunnel construction projects for railway transportation, from Lötschberg Base Tunnel, Gotthard Base Tunnel in Switzerland and Marmaray Tunnel in Turkey to Channel Tunnel between France and United Kingdom.

2.2.3. Tunnel Construction Methods

There have been many developments in type of tunnel constructions to improve the practices and respond to specific needs of different constructions. Type of these methods varies due to ground properties, safety requirements, above ground conditions, construction time and costs. The common types include Cut and Cover, New Austrian Tunneling Method (NATM), Shield Tunneling, Tunnel Boring Machine (TBM), and Drilling and Blasting. Other types include Pipe Jacking, Jacked Box Tunneling and Immersed Tube Tunneling methods.

In this section, three main groups; Cut and Cover, NATM and Shield Tunneling methods will be detailed further however, Garry (2012) can be examined for description of other mentioned methods.

2.2.3.1. Cut and Cover Tunnels

The cut-and-cover method provides an alternative tunnel construction technique which involves; construction of the tunnel structure in a trench or with braced excavation (named as cut) and then it is backfilled (named as cover). For constructions close to ground surface or in locations with no important constraints, this method provides a more practical and economical option for shallow tunneling with depths between 10-15 meters (Chapman et al., 2010).

There are two forms in this construction type; the bottom-up method and top-down method. For less congested sites, the bottom-up method is preferred where the excavation can be done from the ground surface with the sides supported. The construction is carried out within this excavation and when finished is backfilled and the surface is reinstated. Alternatively, in the top-down method, the support walls and cap beams are constructed first from the ground surface by using diaphragm walls or piled walls. Then the tunnel roof is constructed with access openings. The area left from these access openings are reinstated and the construction below the roof continues from these openings. After the construction of cut-and-cover sections, the portions of tunnel excavation are usually carried out by using various other methods like NATM or TBM methods.

In metro constructions, it is common for stations to be constructed by one of the above described cut-and-cover methods. However, especially in urban areas due to space limitations for access shafts, surface traffic and infrastructure diversions, costs can rapidly increase. Therefore, selection between tunnel boring and cut-and-cover methods is made after a careful assessment. The tunnel boring construction methods provides less disruption to traffic and surrounding environment as all the work takes place below ground surface.

2.2.3.2. The New Austrian Tunneling Method (NATM)

The New Austrian Tunneling Method (NATM); was claimed to be originally developed 1950's in Austria by Ladislaus von Rebcewicz, Leopold Müller and Franz Pacher. Its name was first introduced by Rabcewicz in 1962 (Garry, 2012). The method works on an observational procedure where it principally allows the ground to deform between two linings to stabilize the tunnel itself. Geotechnical instruments are installed to measure the deformations and stress distributions within the rock mass. Some of the main principles of the method as given by Müller and Fecker (1978) are listed below:

1. The tunnel is constructed by sequentially excavating and supporting the tunnel. The process depends on the response of the ground therefore, every deformation of the excavation is measured. It is essential to monitor the performance of the excavation, the deformations of the ground and of the initial support, as well as to verify the initial support design and change it if necessary.
2. Typically, the tunnel cross section is divided into a number of smaller faces; usually two or three sections (crown-heading, bench and invert). This number can be increased depending on the cross sections or poor ground conditions.
3. The ground is the main support to the excavated tunnel. The rock mass determines the support measures that need to be adopted. The constructed support system usually consists of shotcrete, reinforced with fiber or steel mesh in combination with rock bolts or fore poling. The shotcrete thickness is optimized based on the monitored deformations.

4. The strength of the rock mass is aimed to be preserved. The support should have suitable stress-deformation properties and its installation should be adequately timed.
5. The support should not be too stiff or too flexible and the loading should not be applied too early. If the support is too stiff, it will carry more load and the ground won't be able to deform until the equilibrium is reached.
6. As for the timing, when same support is loaded after deformation occurs, it will reach the equilibrium with a lower load. Therefore, the support should not be loaded too early; in order to take the advantage of the reduction in load in the support, nor too late in order not to increase the deformations drastically.
7. The invert should be closed as soon as possible to create a load-bearing ring.

This observational methodology of the NATM technique, enables immediate revisions in construction details and makes the method more flexible and a more economical solution compared to the methods having to install the worst case situation support systems throughout the tunnel.

2.2.3.3. Shield Tunneling

As previously mentioned, Shield Tunneling was first developed by Brunel in 1825 however, it was after 1953 that the method found a wider use in the construction industry (Chapman et al., 2010). The mechanized shield method is a tunneling technique in which a steel shield driven in the ground is used to support the face and ground from collapsing while the excavation and lining works are performed (Figure 2.3). It is used for softer soils and weak rocks that require radial support.

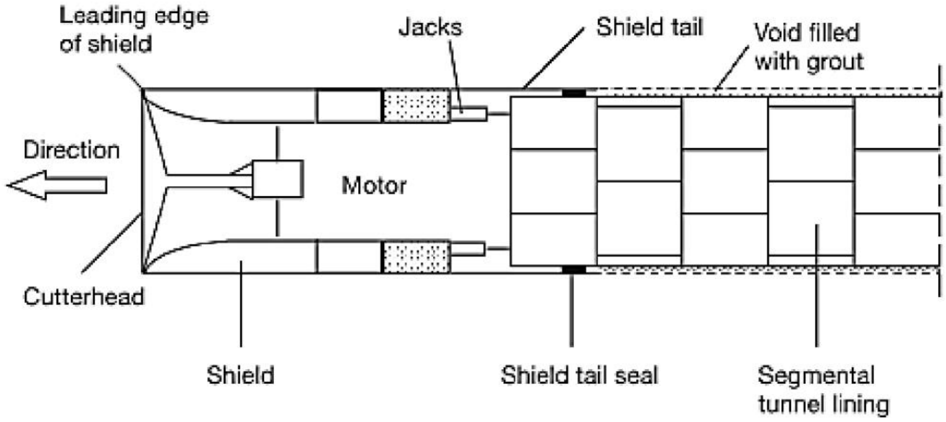


Figure 2.3. Typical Longitudinal Section of Tunnel Shield (Chapman et al., 2010)

Generally, shielding starts from a starting shaft and the tunnel is constructed by the cyclic works comprising; excavation with the rotating cutterhead, installing jacks in the shield to push the shield away from the lining of concrete segments, placing the segments assembled in arc shape. In order to create the necessary force to move the tunnel shield forward, the hydraulic jacks are pushed out against the last erected tunnel segment and the shield against the tunnel face in the direction of tunnel excavation.

The shield methods that are used in practice nowadays are; open, partially closed and closed type shields which differ according to the excavation method and the opening of the cutterhead. The two mostly used TBM's namely Slurry Shield and Earth Pressure Balanced (EPB) TBM's are mechanized examples of closed type shields. A more detailed information on TBM's are given in the following section.

2.2.3.4. Tunnel Boring Machines (TBMs)

TBM is a machine used to excavate tunnels with a circular cross section through variety of soil and rock classes. TBM typically consists of a rotating cutter head, a main bearing, a thrust system and trailing support mechanism (Figure 2.4).

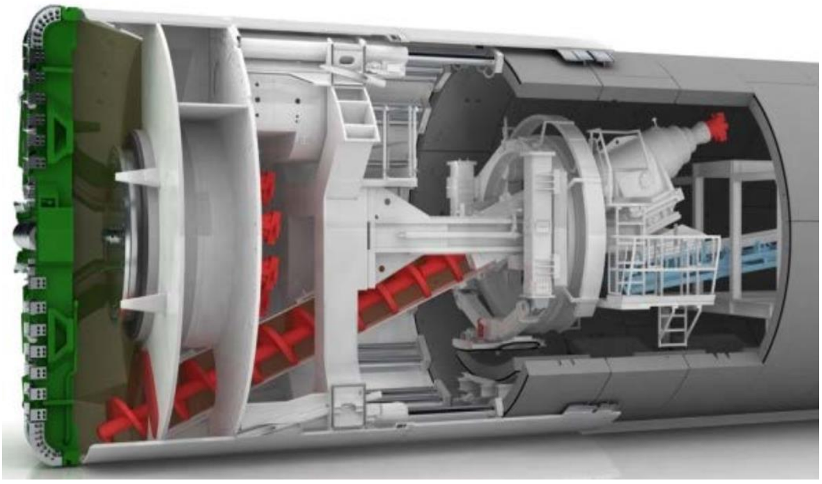


Figure 2.4. EPB TBM Machine Mechanism (Burger and Herrenknecht AG, 2016)

The development of TBM's went together with the development of railroad tunnels in the first half of the 19th century (Section 2.2.2). Between years 1846-1930, many hard-ground tunneling machines were designed but unfortunately, much of those could not be actually built. The Frejus Tunnel by Henry Maus is one of the first attempts for building a rock-tunneling machine for railway tunnel constructions (Garry, 2012). It was built in 1846 for construction of the Fréjus Rail Tunnel between France and Italy crossing through the Alps however it was broken down and was never actually used again to finish the project. The tunnel was later constructed with more conventional construction methods and completed at 1871 (Pelizza, 1999a).

During the same period, in 1853 another pioneering tunnel boring machine was built in United States for the construction of the Hoosac Tunnel (Garry, 2012). In 1875 the Beaumont machine and in 1880 the Beaumont/English machine were patented which were actually used for soft rock tunnel boring, but the construction stopped due to military oppositions (Kirkland, 1986). In 1952-53 the first mechanical rotary excavator was designed and manufactured with 7.8 m. diameter by an American Company, James S. Robbins and Associates (Stack, 1982). It was then developed into the modern rock TBMs with technological advancements.

The main advantages of TBM type tunnels in urban areas lie due to their very little disruption to ground surface. For railway lines it becomes especially important as these projects usually involve time consuming and expensive utility diversions and demolition of existing infrastructures. However, as the tunnel alignments pass deeper under the surface, ground settlements and waterways require much more careful examination both before and during tunnel construction. Therefore, advanced ground investigations become obligatory and crucial to prevent and mitigate impacts of such conditions. The modern methods contain different types of techniques for mechanical support, from open type TBMs and Earth Pressure Balance TBMs to shielded TBMs.

Hard Rock TBMs: These machines excavate rock material with the cutting disks mounted in the cutterhead. Basically, the compressive stress applied by these disk cutters on tunnel face separate the particles from the main rock. The excavated material (muck) is transported on conveyor systems outside the tunnel. TBM moves forwards with the help of a gripper system by pushing itself against the side of the tunnel. Open type hard rock TBMs include ground support systems such as rock bolts, shotcrete and wire mesh for bracing. On the other hand, shielded hard rock TBMs installs concrete segments behind the machine and uses these to support the tunnel walls.

Soft Soil TBMs: These type of TBMs moves forward by pushing itself against the erected concrete segments. As in hard rock TBMs, the soil is excavated by disk cutters from the tunnel face. The excavated muck in soft soil TBMs is transferred through openings in the cutter head to a belt conveyor and removed from the tunnel. Soft soil machines have mainly two widely used types namely Earth Pressure Balance (EPB) and Slurry Shield.

- In an EPB TBM, the muck is held in a sealed chamber behind the cutterhead. The stability of the cut face during tunneling is maintained by balancing the earth pressure in the chamber, rate of removal of excavated material and machine’s advance rate. Due to this mechanism, EPB is mainly used for flowable soil conditions and finer grained sands and silts for the ability to move the excavated muck from cutter chamber to the conveyors such as soft silt and soft clay. However, for unflowable soils or hard and abrasive ground conditions, additives or hard face plates are used (Babendererde et al., 2005).

- The slurry shield TBMs are similar to the EPM machines however, in slurry machines a bentonite slurry is filled into the cutter chamber. Slurry is supplied from treatment plant to the tunnel face with slurry pipe then used to fill the cutterhead chamber. The pressure of the slurry mix stabilizes and supports the tunnel face. The excavated material particles are moved to the slurry chamber therefore slurry also acts as a transport medium for the muck removal. The slurry mixed muck is pumped out of the cutterhead to a slurry separation plant, usually outside of the tunnel, through a discharge pipe so that the separated slurry can be re-used in the tunnel. Due to this process, these type of TBMs are generally better for more coarse-grained sand, gravely soils and not suitable for soils with particle sizes smaller than slurry's bentonite like silts and fine clays. They are more preferred in soils with high water pressure and large amount of ground water. Moreover, generally there are additional area requirements in slurry shield TBMs for bentonite recycling surface treatment plants and a caisson system at the cutterhead for inspection and maintenance of tunnel boring.

2.2.4. Risk Assessment in Tunnel Construction Projects

Tunnel constructions are usually large, complex, and expensive infrastructure projects that involve various risks due to uncertain nature of the underground conditions and highly technical operations. Therefore, a careful risk analysis together with a systematic risk assessment is of high importance to prevent potential losses, analyzing, controlling and mitigating risks in tunneling projects.

The International Tunneling Association (ITA) identified different phases for implementation of risk management in tunnel projects and guidelines on how to utilize the risk management methods in each of these phases from early design to construction stages (Eskesen, 2004). In the study of Sturk et al. (1996), the authors adopted four steps in risk management; hazard identification, assessment of probabilities, assessment of consequences and finally calculation of risks for alternative risk treatment measures to choose among. They have utilized the Analytical Hierarchy Process (AHP) for ranking alternative tunnel ground support methods in terms of cost, feasibility and environmental concerns. The final decision among the alternatives was decided after calculation of the highest expected outcome using fault tree analysis method with case study of tunnel construction projects.

Reilly (2000) identified the main problems of public underground projects as; limited time and resources available to adequately determine underground conditions and bidders to assess construction methodologies during the procurement phase. A management plan of complex underground projects was advised for a more strategic approach in planning, site investigation, designing and construction phases, together with a more integrated project team, and a better, more sophisticated risk identification, analysis and mitigation process. The author suggested that, qualifications of construction bidders should be evaluated more carefully for executing underground tunneling projects compared to the low-bid approaches applied.

In Eskesen et al.'s study (2004); alternative risk management stages were proposed that adopts a four step qualitative approach. Their suggested process follows the project stages.

- In early design stage; qualitative risk assessment shall be carried out by risk identification according to different parties, risk analysis, determining risk acceptance criteria and the risk measures for risk elimination and acceptance. A fault tree analysis of causes of the hazards, and an event tree analysis of the consequences is recommended. In terms of risk mitigation, cost-benefit ratio is proposed for deciding between alternative mitigation measures.

- In tendering and contract negotiation stage; the qualitative risk assessment is advised to be repeated in light of the final tender documents. This stage becomes important for tendering or appending and modifying risk clauses in the contract.
- In construction phase; the retained risks are planned to be managed continuously by the contractor.

Reilly (2005) starts his paper by critical evaluation of the risk assessment methods and development of a better cost estimating methodology for large tunnel construction projects. It has been found that;

- There is a general failure to adequately recognize the uncertainties in estimating future cost or schedules.
- The uncertainty must be included in the cost estimating process.
- Costs must be validated by experienced, qualified professionals who understand the actual bidding and construction procedures.

Large projects often experience large scope and schedule variations, which affect the final cost. Thus, including this in the cost estimates and project management is noted to be important for project success. The author defined a Cost Estimate Validation Process that carries out a probabilistic risk analysis procedure for determining project's "range of probable cost and schedule".

Yoo et al. (2006) developed a GIS-based third-party geotechnical risk assessment system named IT-TURISK, using artificial neural network method for examining change of ground conditions in tunneling works. The model retrieves input from four different risk sources; site information, ground movement, utility assessment and groundwater assessment.

Since the underground constructions are accepted to be governed by the ground conditions, similar to Yoo et al. (2006) most of the risk assessment literature has focused on geotechnical risks or safety risks in tunnel projects. Kim (2008), Hong et al. (2009), Zheng and Ma (2014), Deng (2018), Deng et al. (2018), Guo (2018), Liu et al. (2018), Xia et al. (2018) and Koopialipoor et al. (2019) have used different risk assessment methods from event trees, analytical neural networks to fuzzy methods to evaluate these risks for different tunnel projects.

Fouladgara et al. (2012) employed a fuzzy based "Technique for Order Preference by Similarity to Ideal Solution" (TOPSIS) method for estimating the health, safety and environmental risk factors in tunneling, considering complex effects and stated that various risk factors can be expressed by a "stability and environment index" using numerical and statistical analysis. Their research is based on the basic concept of TOPSIS, developed by Hwang and Yoon (1981) which can be summarized as; the chosen alternative should have the shortest distance from the positive-ideal solution and the farthest distance from the negative-ideal solution. They identified collapse as the highest risk factor in tunnel projects.

More specifically, TBM, as a kind of common tunnel construction equipment provides advanced techniques and equipment to aid underground engineering, however, at the same time would cause grave consequences if the construction risks are not properly assessed. Therefore, Sousa and Einstein (2012), used BBN method to assess the geological risks and provide a prediction model for TBM tunnel projects. They used ground condition data along the tunnel excavation alignment to analyze the risk of tunnel face collapse and provide decision makers a choice among open or closed modes for an EPB TBM. However, this study only considered a single risk event and a rather limited variety of alternatives.

When literature on tunnel projects are examined the common risks for TBM constructions have been listed as; tunnel collapse, gripper or support failure, workforce safety failure, large amount of backfill, cutterhead getting stuck, segment damage, geological structure, experience of workmanship, flooding or explosive gas leakage. Among these risk sources, the geological risks, equipment risks, and workmanship risks constituted 40%, 30% and 30% of the construction risks respectively (Kui and Huanhuan, 2013).

Cardenas et al. (2014) focused mainly on the construction stage of tunnel projects in terms of "deformation/damage of concrete lining". Major risks during the construction phase were identified according to the literature survey and expert views and a BBN was created accordingly. It was seen that "excessive ground movement," "inadequate nominal stiffness of lining," and "damage to rings" were the most important factors. The research showed that, in spite of the complex and ambiguous nature of construction risks, the risk assessment models that can induce the risk related knowledge can be used to obtain valuable project guidance.

Nezarat et al. (2015) implemented a Fuzzy Analytical Hierarchy Process (FAHP) process to determine the geological risks of tunneling projects. The method had been used by other researchers for; decision making, assessing tunnel fire risk of subway lines by combining the fuzzy consistent matrix and AHP.

In the study, although AHP method was chosen as basis due to its ability to provide breakdown of the problem in a hierarchical form and comparison of the considered options; referring to the criticisms on its use of unbalanced scale of judgments, inability to adequately handle the inherent uncertainty and imprecision in the pair-wise comparison, a FAHP method was proposed for determining the main risk factors in tunneling projects. According to the analysis on a case study tunnel project, it has been found that squeezing and face tunnel instability have the highest geological risks. These are followed by groundwater inflows and the instability of wall. Whereas; clogging of clay, swelling of rocks, mixed ground conditions and gas emissions had the lowest level of risk.

Naghadehi et al. (2016) first addressed the need for an efficient risk analysis method for tunneling projects due to high levels of uncertainty in geological conditions that is especially a determinant factor in these types of projects. The authors introduced "Decision Aids for Tunneling (DAT)" tool based on Monte Carlo simulation method.

They have developed a series of probabilistic geotechnical profiles corresponding to different ground classes. As a result of the method developed, each simulation evaluates conventional and mechanical excavation methods and gives an output in terms of project time and cost.

Mao and Zhang (2017) and Siang et al. (2017) gathered the important risks that are involved in tunnel projects.

Later on, a more comprehensive research on risk assessment of tunnel projects was conducted by Forcael et al. (2018). They have identified a comprehensive inventory of risk factors governing the tunnel projects (Table 2.1). Although they have focused solely on the financial aspect of risks, their most notable finding was that; imprecise cost estimations, unexpected geological conditions, incorrect schedule estimations, mechanical/equipment failures, approval processes in government authorities and design changes are among the most critical risk factors.

Table 2.1. *Risk Factors for Tunnel Projects (adapted from Forcael et al., 2018)*

Risk Category	Risk Factor
Contractor	Poor contract management
	Inaccurate cost estimation or lack of detail in budget preparation
	Inaccurate deadline estimation or insufficient breakdown of the project schedule
	Financial difficulties of the constructor
	Inadequate project scheduling
	Errors during construction
	Operating costs higher than estimated
	Hazardous working conditions (danger of accidents)
Project Designer	Variations in the original design (required by project designers)
	Inspections and/or testing delays by project designers
	Lack of experience by project designers
	Delays in approval of permits and tests

Owner	Difficulties for paying monthly progresses
	Variations (change orders) in the original design (introduced by owners)
	Type of construction contract
	Methodology of contract award and method for setting fines and bonds
Labor	Lack of labor
	Lack of qualified professionals and technicians
	Nationality of labor
	Low labor productivity
	Lack of skilled labor
Materials and Equipment	Variability of material prices
	Dependence on imported materials/lack of local material availability
	Frequent malfunction of construction equipment
	Suppliers unable to deliver products or services on time
	Low productivity and efficiency of the equipment used
	Materials do not meet technical specifications
Project	Occurrence of disputes between stakeholders
	Lack of communication and coordination among project participants
	Environmental restrictions
	Tunnel depth
External Factors	Lack of information or inaccurate information regarding the construction site
	Unpredictable weather conditions
	Excessive delays in approval processes by government entities
	Unexpected soil conditions and water table
	Unexpected geological conditions

Many researchers point out that infrastructure projects and in particular tunnel projects face cost and time overruns. According to Isakkson and Stille (2005), tunnel projects are more susceptible to risks compared to above ground constructions. Thus, they proposed a probability-consequence risk analysis method for time and cost deviations between different tunneling methods. They have found out that in varying soil conditions, mix shield TBMs show lower time overruns when compared to EPB TBMs due to their adaptability to varying soil conditions.

Han et al. (2009) examined the schedule delays in large infrastructure projects and suggested that the project success is dependent on time control. According to the authors, the schedule delays are the governing factors in achieving desired project performances and are correlated to the cost overruns as well.

Konstantis et al. (2016), identified the risk factors effective on tunnel projects in terms of cost and time aspects and from the insurance field perspective. They have highlighted the risk sources as; geotechnical conditions, tunnel construction methods, design approach, construction execution and workmanship. They also identified the most important failure types in tunnel projects. With respect to the project delays, according to the authors the delay durations in tunnel projects ranged between 1-48 months. In addition, they compared the relation of delays with insurance costs and found out that the linear relation between shows that, when delay durations increase in tunnel projects the insurance costs also increase.

Sherry et al. (2017), also evaluated the time and cost overruns in tunnel projects. According to them, the primary project success criteria is based on meeting cost and time objectives of projects. In line with this, they have used a risk rating system that has dimensions in terms of both project cost and schedule impacts. They examined two tunnel alignment alternatives using the risk registers that contain multidimensional scales for geotechnical, financial, legal, environmental conditions, schedule, health and safety conditions. The method is used to decide on the most advantageous alignment alternative based on the most favorable ground conditions.

Another important contribution for schedule risk assessment in tunnel projects was carried out by Yu et al. (2017). They developed a probabilistic model for diversion tunnels that follow the sequence of TBM excavation operations; TBM relocation, boring, muck removal, advancing, shifting, installation works, etc. Using the construction schedules, they estimated the probability of occurrence of risks in Bayesian networks and then used these probability distributions in Monte Carlo simulations, to calculate the probability of completion of TBM excavations within planned durations. They have found out that although geotechnical conditions dominate the probability of occurrence of risk events, design and management performances influence achieving the planned project schedules.

In light of these studies, it can be concluded that in tunnel projects, delays could reach extreme values and cause critical cost and time overruns, due to the scale and the amount of resources required in these projects. However, even though many researches have been conducted for implementation of risk assessment methods in tunnel projects, they have been concentrated on a specific aspect among the various risk sources. Many methods have been utilized but BBNs have proven to be the most advantageous for incorporating different risk events, their interrelations and overall impact on project performance.

2.3. PROJECT RISK ASSESSMENT AND MANAGEMENT

Risk management is one of the ten project management knowledge areas described in Project Management Body of Knowledge (PMBoK) and described as the process of planning, identifying, analyzing, response planning and controlling project risks (PMI, 2013). The risk assessment section includes identification and analysis stages (ISO, 2009). According to PMI (2013), as this assessment step is based on the collected risk data, it becomes necessary to carefully analyze and manage the information gathering process.

The main objective of this research is to develop a systematic methodology for delay risk assessment of tunnel projects through an extensive risk taxonomy and a mathematical analysis method. In order to start the procedure with a clear standing point, a unified glossary of risk management terms is seen as an important step for commencement. Therefore, this section will start with the definitions of the mostly used risk assessment and management concepts for the construction industry.

2.3.1. Risk Assessment and Risk Management Concepts

Uncertainty is the source of risk in all engineering enterprises, and refers to the event with an unknown parameter such as occurrence, impact, possible outcome etc. (Rahman and Kumaraswamy, 2002). According to Raftery (1994), the word "uncertainty" is used where it is impossible to describe a situation in terms of probability of occurrence of an event.

The term of risk has origins from the French word "risqué" and became known in English language in 17th century. The primary meaning of the word came from the Spanish sailing term for difficulty in avoiding danger/rock in the sea (Jannadi and Almishari, 2003) and later has found its first use in 18th century for insurance operations (Zachmann, 2014). It is defined in the literature from two different perspectives; either with only a negative impact or with an impact that can be negative or positive on project objectives. Leaning towards the first perspective; Chapman (2001) defines the term as "likelihood of occurrence and the degree of impact of a negative event adversely affecting an activity" and Cardenas et al. (2014) refer it as "a potential failure event".

For a broader definition; risk is the probability that an adverse event occurs during a stated period of time (Royal Society, 1992). Conforming with the latter perspective; risk has been referred as a combination of the probability, severity and exposure of all hazards of an activity (Jannadi and Almishari, 2003). Rausand (2011) defines the term as "the chance of something happening that will have an impact on objectives" whereas Fouladgara et al. (2012) defined risk as a function dependent on the parameters; likelihood, consequence, and reaction against an event (Fouladgara et al., 2012). Combination of these terms; PMI (2013) defines risk as an uncertain event or condition that, if occurs, has a positive or negative effect on a project objective. In practice it is widely known as the product of impact of an event and its probability of occurrence (Reilly, 2000).

The term “vulnerability” is sometimes confused with the term “risk” (Ezell, 2007). Compared with the definition of risk in the literature, vulnerability represents the capacity of a system to cope with a risk event (Zhang, 2007). Like risk, vulnerability was defined by various researchers in the literature. Blaikie et al. (1994) describes the term as “a characteristic of a person or group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard”. Fouladgara et al. (2012), claimed vulnerability as any weakness that can convert a potential hazard into an active hazard. Whereas, Zhang (2007) claimed that vulnerability of a system represents the extent or the capacity to respond or cope with a risk event.

Risk sources are factors that can have negative impacts on a project. In a wider perspective it is an “item or activity having a potential for a consequence” (ISO, 2002). In Standards Australia and Standards New Zealand (2004), it is a source of risk that can potentially harm the subject.

Risk events/hazards on the other hand, are occurrence of a negative happening; which leads risk factors to risk consequences (Al-Bahar and Crandall, 1990; Zhang, 2007). Risk event is also described by ISO (2002) as “occurrence of a particular set of circumstances”. According to Standards Australia and Standards New Zealand (2004), it provides connection between the risk sources and the anticipated impacts.

Risk impact/consequence is the outcome of an event (Fouladgara et al., 2012). Reilly (2000) defines the term as the effect, on a project or its objectives that is measured in terms of safety, cost, schedule delay, quality of construction, or other similar technical aspects. PMI (2013) expands its definition to “the effect on project objectives if the risk event occurs”. It could be an increase in expected costs or perhaps collapse of the entire network. In order to evaluate this, consequence analysis is usually carried out to identify all potential consequences of risk events and also their probability of occurrences.

Risk Management has been accepted to be originated in the 1950's in terms of financial insurance risks. The first known publishes were by Mehr and Hedges (cited in Dionne, 2013), Williams and Hems in the early 1960's (cited in Dionne, 2013). From 1970's the financial risk management started creating formal risk management systems and assessing contingencies (Dickinson, 2001). In the 1980's quantitative risk analysis was emphasized in the risk management arguments and probability distributions and their use in risk modeling were introduced. The process plant and energy systems construction projects were among the first projects to use software-based risk management applications based on probabilistic and sensitivity analysis methods (Artto, 1997). Hayes et al.'s (1986) work has been one of the earliest organized risk management studies in construction industry. Various researchers investigated the use of project risk management processes (del Cano and de la Cruz, 2002). They have recommended considering project scale, complexity and organization's risk maturity level for risk management practices.

According to Flanagan and Norman (1993), Risk Management is "a discipline for living with the possibility that future events may cause adverse effects". It was defined in Eskesen et al.'s paper (2004) as the overall term which includes risk identification, risk assessment, risk analysis, risk elimination, risk mitigation and control. Dikmen et al. (2004) describe the process as; definition of objectives in terms of certain functions that represent project outcomes, calculating the probability of achieving these aims by assessing different scenarios and finally formulating risk response strategies. Therefore, it is suggested to provide a continuous system to identify risks, estimate consequences scenarios and developing risk response strategies (Dikmen et. al., 2008).

Various studies have proposed the process of project risk management (PRM) for project success, as shown in Table 2.2 (Lee et al., 2009; Boehm, 1991; Chapman, 1997; Cooper et al., 2005; NASA, 1995; Patterson and Neailey, 2002; Tummala and Leung, 1996; Zhi, 1995). Though some studies used a detailed process for specific applications (Kwak and Stoddard, 2004), or a modified process for evaluating the risk ranking of various projects (Baccarini and Archer, 2001), the general project risk management process consists of five phases: risk identification, analysis, evaluation, risk treatment and risk monitoring (Figure 2.5).

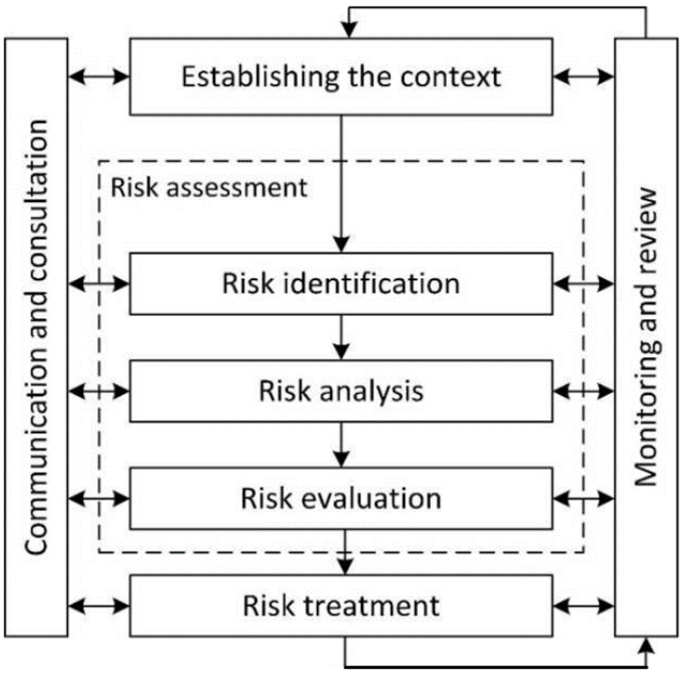


Figure 2.5. Risk Management Process (ISO, 2009)

Table 2.2. *Risk Management Processes (Adopted from Lee et al., 2009)*

	Chapman, 1997	**Cooper et al., 2005**	**NASA, 1995**	**Boehm, 1991**	**Patterson and Neailey, 2002**	**Tummala and Leung, 1996**	**Zhi, 1995**
Field	Various industries	Various industries	Various industries	Software development	Automotive manufacturing	Utility sector	Construction
Stage 1	Define/ focus	Establish the context	Risk planning				Risk classification
Stage 2	Risk identificatio n	Risk identification		Risk identification	Risk identification	Risk or hazard identification	Risk identification
Stage 3	Structure/ ownership Estimate	Risk analysis	Risk analysis	Risk analysis	Risk assessment Risk analysis	System hazard analysis Ranking of hazards	Risk assessment
Stage 4	Evaluate the risks	Evaluate the risks	Risk prioritization Risk management planning		Development of action plans		
Stage 5	Plan			Risk resolution	Risk reduction/ mitigation	Evaluate the risks	Risk response
Stage 6	Manage	Treat the risks	Risk mitigation and tracking	Risk monitoring	Risk monitoring/loop	Risk control and monitoring	

As it would be seen in Figure 2.5, identification is the beginning and basis of the engineering project risk management process; where potential risks, risk sources, and their consequences are recognized and examined (Mo Nui Ng, 2006; Zou et al., 2007; Akinci and Fischer, 1998). It is a process of systematically and continuously identifying, categorizing, and assessing the significance of risks associated with a project. Thus, it consists of analyzing the uncertainty of risk factors, risk sources, risk characteristics, risk events. The most commonly used techniques include brainstorming, document review, Delphi technique, interviews, risk register analysis, and assumptions analysis.

In order to carry out this stage of risk management, Chapman (2001) proposed studying risk relationships by classifying them as, dependent risks that are depicted graphically in series, independent risks that are depicted graphically in parallel. The author suggested utilizing precedence, influence diagrams, knowledge maps or flow charts to represent these relationships. The study of Chapman (2001) is among the important contributions in examining cause-effect relations among risks using risk paths generated to represent the relationships.

Risk path, as defined by Han et al. (2008), is the combination of risk variables and their cause-and-effect scenarios, which made up "tree structures of risk courses". Han et al. (2008) analyzed the causality between risk variables, sorted them as risk sources and events with respect to their hierarchical order and constructed series of risk paths from its source to event, to corporate a risk checklist. They can be defined as figurative representations of the correlation between risk causes and effects through a risk network (Dikmen et. al., 2008). The network connects these risk causes to risk consequences to show the overall impact of risks on the project outcomes. Kim et al. (2009) also proposed a path diagram for demonstration of relationships and interactions among 64 performance influencing risk variables and 14 major variables directly affecting project performance.

Many other researchers evaluated the necessity of modeling risk sources, consequences and factors that affect magnitude of risks (Dikmen and Birgönül, 2006; Dikmen et al., 2004). Tah and Carr (2001) used “influence diagramming method” for instance, to model the relationships between risk sources and influencing factors.

Han and Diekmann (2001) noted; the difficulties in using intuition-based analytical methods for complex problems, high amount of data required in statistical approaches, complicated calculations involved in decision trees, sensitivity of neural networks to data sets, and high amount of detail required in representation of relationships in influence diagraming methods. Therefore, they developed a “cross impact analysis” method to help decision-making processes in projects. However, in the following years Weimer-Jehle (2006) criticized this cross-impact method, due to its demand for complex expert elicitation in conditional probability assignments.

According to Figure 2.5, the second stage in risk management is the risk analysis, which can be described as a structured process that identifies both the likelihood and consequences of risk events (Zhang, 2007; Summers, 2000). As also given in PMI (2013), the risk analysis phase can be divided into qualitative and quantitative risk analysis for evaluation of risk impacts and their probability of occurrence (Mo Nui Ng, 2006).

Qualitative Risk Analysis Methods: According to PMI (2013), these methods assess and evaluate the project risks and prioritize these risks according to certain criteria. The qualitative risk analysis includes evaluating important information about risks such as probability of occurrences, severity and ownership of risks. It is usually assessed through a probability and impact matrix using a pre-defined qualitative rating scale. The matrix form is constructed by defining the probability of occurrence of an event versus the impact that are defined commonly in a linguistic scale from low to high. Some other common qualitative risk analysis techniques include risk registers, checklists, what if analysis, failure mode and effect analysis and hazard and operability analysis. Eventually these techniques lead to quantitative analysis processes (Alverbro et al., 2010).

Quantitative Risk Analysis Methods: In a quantitative risk analysis, the possible outcomes of project risks are calculated and as a result, the probability of achieving specific project objectives is assessed. It involves a detailed analysis of the highest priority risks, through numerical rating or probabilistic analysis methods. One of the most common quantitative methods is the utilization of Monte Carlo simulation (Eskesen et al., 2004). In this method usually, the duration or costs of a project are represented by probability distributions. By conducting numerous iterations, a probability distribution of possible outcome is obtained for a target project objective. In the sensitivity analysis section, the sensitivity of the project to different risks are evaluated by calculation of their effect, usually in terms of duration or cost of the project. Other widely known analytical and quantitative methods involve decision tree analysis (DTA), influence diagraming, event tree analysis (ETA), fault tree analysis (FTA), Bayesian belief networks (BBN), fuzzy theory (Kuchta, 2001), markov methods and petri nets (Rausand, 2011).

In DTA, the project is graphically modeled identifying possible risk factors, their probability of occurrences and impacts on the project outcome (Eskesen et al., 2004). As a result, the most probable and the most beneficial outcome can be examined. Influence diagrams are also graphical representations of project risks, which help formulating problems in decision-making. However, these diagrams could get quite complex and require computational efficiency (APM, 2004). Similarly, ETA provides representation of logical order of events arising from one or more causes and leading to consequences. In an ETA the network starts from an initiating first event and develop from there until all possible states are fulfilled. Probability assessments of each event provide a quantitative analysis (Molak, 1997; NASA, 1995). FTA on the other hand, is used to analyze the causes of a single undesirable event. In a fault tree (FT) different node shapes are used to illustrate different roles. The undesired event such as an economic loss or accident is placed at the top of the tree structure. The rest of the network is constructed downwards from primary events in a causal structure with binary states. In the analysis part, the probability of the top event is calculated from the probability of occurrence of intermediate and primary events. Thus, large and complex FTs need computer aided analysis methods such as Monte Carlo simulation or binary decision diagramming or fuzzy set theory. The main drawbacks of FTAs are the inability to use multi-state variables and more than one output event. In this context, the Bayesian Belief Networks (BBNs) provided a more suitable alternative in quantitative risk analysis (Bouissou and Pourret, 2003).

Bayesian Belief Networks are directed acyclic graphs consisting of nodes, arcs and conditional probability tables that are assigned to the nodes that represent the degrees of influences of each node on one another. They have been mostly utilized in systems reliability, risk assessment and safety analysis literature. To broadly define BBNs, the root nodes represent conditionally independent variables whereas the remaining nodes are conditionally dependent on their direct parents (Jensen and Nielsen, 2007). More detail on its theoretical background and calculation principles are provided in Section 2.3.4. However, here it should be noted that translation of fault trees to Bayesian networks possess an important part in the literature. Castillo et al. (1997), Portinale and Bobbio (1999), Bobbio et al. (2001), Mahadevan et al. (2001), Qian et al. (2005), Xiao et al. (2008) and Franke et al. (2009); contributed in translation of FTs to BBNs. The initial work on this area is presented by Torres-Toledano and Sucar (1998) who explained the translation from one representation to the other. The mapping algorithm proposed by Khakzad et al. (2011) is given in Figure 3.2. As seen in the figure primary events, intermediate events, and the top event of the FT are illustrated as root nodes, intermediate nodes, and the leaf node in the BBN, respectively. The connection between nodes are preserved in the BBN.

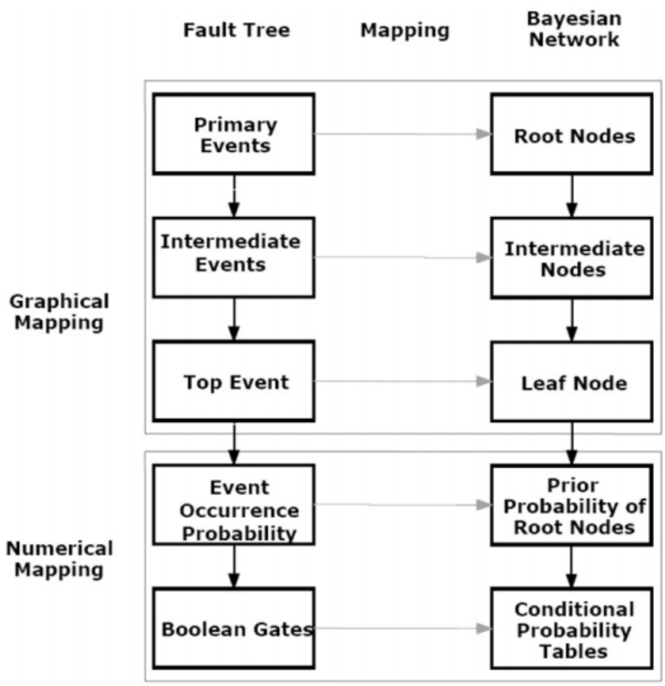


Figure 2.6. Mapping form FT to BN Model (Khakzad et al, 2011)

According to Figure 2.5, Risk Assessment is the combination of identification, analysis and evaluation steps. It involves systematic use of available tools to identify risk events and to estimate the effects of risks on individuals, properties, environment, project success and comparison of the consequences of risk analysis with certain acceptance criteria, other available decision parameters (Zhang, 2007). Therefore, the next step in risk management involves the risk evaluation phase. In this stage, the risk analysis results are compared with certain predetermined criteria, to determine if the calculated risk level is acceptable or not. This process usually combines the strategic objectives of companies, time and budget constraints and employer demands. To integrate this procedure into project or company the strategies, and assessment of risks that are more significant for the projects, strategic risk assessment is defined as evaluation of the most critical risks in a systematical and continuous process (Frigo and Anderson, 2009). This process is aimed to identify the strategic risks and required action plans to handle these risks. The process involves the following steps; identify the strategies, gather data on strategic risks, determine the strategic risk profile, develop an action plan, communicate and implement the developed action plan.

In the following step, the risks identified as unacceptable are examined for risk treatment. Risk treatment is defined as identifying options, selecting and implementing measures to modify the project risks. It is utilized for avoiding, transferring, retention or controlling risks, their impacts, severity and probability of occurrence (Reilly, 2000; Mo Nui Ng, 2006). Among these treatment options, risk avoidance involves changing part of the project to make sure the threats cannot happen or do not affect the project anymore. In risk transfer, the impact is reduced through measures like insurances or adding contract conditions like penalties. Risk retention on the other hand, is the conscious decision for acceptance of low impact, low probable risks due to the fact that taking preventive actions may be costlier than the cost of any potential loss. Finally, in risk reduction the probability of impact of the risk is aimed to be decreased.

As the main purpose of this thesis is to develop a BBN based risk assessment methodology, the next section of this chapter will give a summary of the theory on BBNs and its applications in the risk assessment literature.

2.3.2. Bayesian Belief Networks for Risk Assessment

2.3.3. Bayesian Probability

2.3.3.1. Basic Summary on Probability Theory

Statistics in brief deal with uncertainty due to variability in data. According to Jensen and Nielsen (2007) the basic probability theories can be given as follows;

- For the sure or certain event S; $P(S) = 1$
- For every event A; $0 \leq P(A) \leq 1$
- If A and B are any two events, then; $P(A \cup B) = P(A) + P(B) - P(A \cap B)$

- If A and B are mutually exclusive events, then; $P(A \cup B) = P(A) + P(B)$

There are two main approaches in statistics namely; frequentist (classical) approach and Bayesian approach. In frequentist approach, probabilities are related to all possible random samples (Bolstad, 2007). They represent the physical world. In this approach, parameters are considered to be a fixed but unknown constant. For equal probability of events, $P(A_k) = 1/n$ (where $k = 1, 2, \dots n$) (Jensen and Nielsen, 2007).

On the other hand, in Bayesian approach, probability of an event, is a person's "degree of belief", therefore it represents the person who assigns the probability. In the Bayesian approach, probability distributions are subjective. This approach is based on the principles that are explained in the forthcoming section.

2.3.3.2. Bayes' Theorem

The Bayesian Theorem was developed by Rev. Thomas Bayes, an 18th century English mathematician and statistician. The publication "An Essay Towards Solving a Problem in the Doctrine of Chances" introduced the theorem for calculating conditional probability distributions given a set of interacting variables (Bernardo and Smith, 2000). It is based on the "Bayes' Rule" that restates the conditional probability $P(A \backslash B)$ for updating beliefs about an event (A) given information about another event (B) (Jensen and Nielsen, 2007). In conditional probability rule, any probability of an event is based on the statements that are already known.

$$P(A \backslash B) = \frac{P(A \cap B)}{P(B)}$$

(Equation 2.1)

Probability of occurrence of an event named as P(B) depends on the probability of occurrence of another event A and their occurrences together. When the events A and B are independent; $P(A \backslash B) = P(A)$, then the fundamental rule is rewritten as $P(A \cap B) = P(A \backslash B) \cdot P(B) = P(A) \cdot P(B)$. That is, we can calculate the probability that both events will occur by multiplying the probabilities for the individual events. As indicated in the previous section, in Bayesian statistics, probability statements about parameters are represented as “degrees of belief”.

$$P(A\backslash B) = \frac{P(B\backslash A) \bullet P(A)}{P(B)}$$

(Equation 2.2)

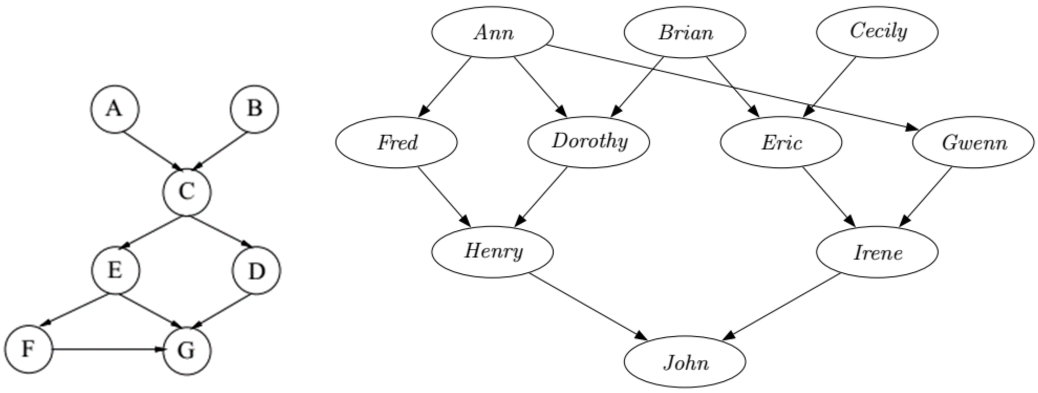
P(A) is called the prior probability of A; which is the initial degree of belief. P(A\B) is called the posterior probability of A given B or the degree of belief in A having considered for B. Similarly, the probability P(B\A) is called the likelihood of A given B. The Bayes’ theorem is a further combination of conditional probabilities. It enables updating beliefs about an event A, given that there is information about another event B. It can be updated, in the light of new and relevant data and provides a solution to learning from data. In other words, the Bayes' theorem links the degree of belief before and after accounting for evidence, by defining the relationship between the probabilities of events (p(A) and p(B)), and the conditional probabilities (p(A\B) and p(B\A)) (Lee, 2012). The main advantages of this approach are listed below (Bolstad, 2007);

- The parameters can be random variables. The probabilities for parameters can be calculated from observations as well as sample statistics.
- Bayesian statistics can combine prior information with data. The probability rules are used to revise the inference based on the actual occurring data. Thus, it is a predictive method unlike conventional frequentist statistics. It provides interpretable answers to a wide range of models for finding the conditional probability distributions of a given the sample data.
- Estimations can be calculated directly without reliance on a large sample size.
- Nuisance parameters can be handled. These parameters are parameters that are used for the sake of the analysis that are not considered as primarily meaningful data about the main problem. They are generally not desired to be used for making inference but also not desired to be ignored that would alter the problem

definition. Frequentist statistics does not have a general procedure for dealing with them.

2.3.4. Bayesian Belief Networks

Bayesian Belief Network (BBN)s, also known as Bayesian Network (BN)s have a long history in statistics and can be traced back to the work of Minsky (1963). He used Bayes nets to create a problem-solving mechanism in programming field. The connection between causation and conditional independence was studied by Spohn (1980). In the first half of the 1980s they were introduced in the field of expert systems through work by Pearl (1982) and Spiegelhalter and Knill-Jones (1984). Some of the first real-world applications of Bayesian networks were for disease diagnosis in Munin (Andreassen et al., 1989, 1992) and Pathfinder (Heckerman et al., 1992). Weber (2012) defines Bayesian Belief Network (BBN) as a directed acylic graph (DAG) which captures the Bayes' rule in a graphical model (Figure 2.7.a). In other words, in a Bayesian network, the network does not contain cycles. According to Nasir et al. (2003), it is a graphical representation of conditional dependences among a group of variables.



(a) (b)

Figure 2.7. Bayesian Belief Networks (Jensen and Nielsen, 2007); (a) Directed Acyclic Graph Example, (b) A sample Bayesian Belief Network

A BBN consists of both qualitative and quantitative sections (Gurp and Bosch, 2000). The qualitative section, also named as “structural learning” is the graphical representation of dependencies between variables in the BN. It consists of a set of nodes representing variables and a set of directed arcs illustrating the causal relationships and provides representation of joint probability distributions (Jensen and Nielsen, 2007). The joint probability distributions are represented between parent and children nodes. In larger networks there are root nodes; any node without parents and leaf nodes; any node without children (Figure 2.7.b). The quantitative section on the other hand, called “parameter learning” represent the cause and effect relationships among variables. The BBN uses a probabilistic approach to determine the likelihood of occurrence of a certain variable i.e. nodes. Each node has quantitative probabilistic information associated with it. This probabilistic information consists of two features; i) set of states that contains the events that are probable for that node and ii) a conditional probability table (CPT) that represents the relationship between the node and its parents. When creating Bayesian Belief Networks, the recommended steps are summarized as follows in the literature (Heckerman, 1997):

- Identifying the purpose of the model and defining the problem,
- Determining information relevant to the problem,
- Determining sets of these information for the model,
- Organizing subsets with mutually exclusive and collectively exhaustive variables,
- Assessing local probability distributions for each variable.

Assessing the local probability distributions determines how one node influences the other. Definition of this causal relationships in a Bayesian Network is regarded as the most important step for model success in expert systems (Heckerman et al., 1995a). These data that are defined through the CPTs that are obtained from either empirical/historic data or expert judgments (Leu and Chang, 2013). Reliance on past experience, i.e., prior information forms the basis of the Bayesian Theorem. When

CPTs are determined, the probability for any node can be calculated using the chain rule. According to this, the joint probability distribution, named as P(U), of a network U = {A1, ……., An} is the product of all conditional probabilities that are related to it:

$$P(U) = \prod_{i} P(A_i \text{ I } p(A_i))$$

(Equation 2.3)

where p(Ai) is the parent set of Ai. This calculation effort is rather simple for small problems such as in the case of naïve Bayes models. In a naïve Bayes model, the variables are assumed to be independent (Figure 2.8). Therefore, CPTs become relatively easy to calculate (Jensen and Nielsen, 2007). Naive Bayes was used earlier by de Dombal et al. (1972) and can be traced back to Minsky (1963). If the conditional independence assumption does not affect the probability values of states, then use of these Naive Bayes models are said not to affect the performance of the system.

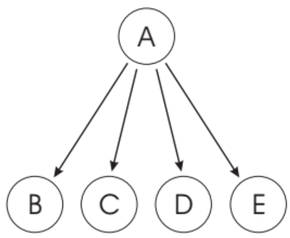


Figure 2.8. A sample Naive Bayes Model

An example is provided in Appendix-A to demonstrate a sample BBN calculation procedure. Further exercises for building and calculation of Bayesian networks can be found in Jensen (1996).

When a variable has several parents, the amount of knowledge to be acquired, number of relations to be model and the computational efforts during calculation of the probabilities increase (Leu and Chang, 2013). For larger networks as depicted in

Figure 2.8.b, the relations become more complex and the calculations become more difficult. In these cases, the root nodes have the simplest CPTs whereas the leaf nodes have the most complicated CPTs, depending on the number of parents involved. To handle this kind of task, Leu and Chang (2013) proposed constructing network hierarchies in FT and then converting them into BBNs. As it is mentioned in Section 2.3.1, several authors contributed in developing such transformation processes. Andreassen et al. (1989) on the other hand, proposed the method called "divorcing the parents". In this method, the network configuration is partitioned into the sets (Figure 2.9).

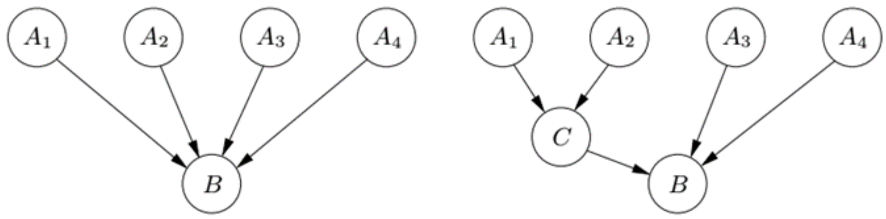


Figure 2.9. Sample network showing divorcing of parents (Jensen and Nielsen, 2007)

2.3.4.1. Advantages of Bayesian Belief Networks

As mentioned before, in classical approach the probability represents the physical property of the world, such as the toss of a coin; whereas in Bayesian approach the probability defines the viewpoint of the person who assigns the probability, such as his/her degree of belief that the coin will land heads. BBNs are representation of this approach, that is based on the opinions of the experts who assign the probability. It is a graphical model that conceals the joint probability distributions of large set of variables. Bayesian networks are essentially mathematical models that model problems with probabilistic data, through graph concepts, to make the problems easier to analyze, implement, and understand (Uusitalo, 2007). Many authors indicated the advantages of BBNs (Cheng et al., 2002; Fan and Yuu, 2004; Heckerman, 1997; Luu et al., 2009; Uusitalo, 2007). Summary of these advantages can be listed below;

- Although more data is better, BBN can handle incomplete data sets and work with the amount of data that is available to achieve accurate results. Thus, the method is also suitable for small and incomplete data sets.
- BBNs combine the strength of causal relationships with probabilities and use empirical knowledge and expert data.
- Its network structure enables understanding relationships between variables.
- Once a model is compiled, resultant probabilities can be obtained quickly through already established CPTs. Thus, computational effort is rather low to get results in a BBN.
- BBNs allow a variable to be entered as evidence and calculate the output from the model. When new "evidence" is obtained, the probability can be induced into the graphs by updating the nodes. Therefore, it becomes possible to update prior knowledge with new information and combining data from different sources. After each entry, the models learn and refine to give better results. Thus, they allow learning from causal relationships that is especially useful in understanding the problem domain, studying macro systems and making predictions under changing circumstances. It is therefore, applied to decision support systems with uncertainty. Authors refer BBN as a powerful tool for knowledge representation, reasoning under conditions of uncertainty.
- It also allows adding or removing variables from the model without significantly affecting the network structure.

2.3.5. Bayesian Belief Networks for Risk Assessment

The original BBN method utilized by Pearl (1982) is one of the most influential methods in knowledge representation and decision making especially for complex problems. BBNs' underlying theory Bayesian probability has been known for a long time; however, its implementation and use in software tools are available in more recent decades (Jensen, 1996). Since then the method has been widely applied in real-world problems such as; computational problem diagnosis, troubleshooting and decision support (Burnell and Horvitz, 1995; Fenton and Neil, 1999; Heckerman et al., 1995a; Heckerman et al., 1995b; Jensen, 1996; Ziv and Richardson, 1997), disease diagnosis (Andreassen et al., 1989; Andreassen et al., 1991; Franklin, et al., 1989; Heckerman et al., 1992; Lauritzen et al., 1994; Xiang et al. 1993), handling computer data (Binford et al., 1989; Jensen, Christensen and Nielsen, 1992; Levitt et al.; 1993; Munck-Fairwood, 1992), information processing (Bruza and van der Gaag, 1993; Horvitz and Barry, 1995), agricultural prediction systems (Rasmussen, 1995; Jensen, 1995), weather forecasting (Abramson et al., 1996).

The method has been extended to management and engineering fields; in transportation (Ulegine et al., 2007), ecosystem and environmental management (Stewart-Koster et al., 2010; Uusitalo, 2007), software risk management (Fan and Yuu, 2004), system reliability (Doguc and Ramirez-Marquez, 2009; Marquez et al., 2010), safety risk assessment (Leu and Chang, 2013). BBNs have also been used in accident scenario analysis, additional to other methods preferred such as fault tree (FT) analysis, event tree (ET) analysis, Petri nets, Markov chains and neural networks (Nivolianitou et al., 2004; Weber et al. 2012). In Khakzad et al.'s study (2011) the major advantages of BBNs over fault trees are claimed to be due to its modeling and analysis capabilities. In the specialized literature about BBN, Weber et al. (2012) examined 200 articles on application of BBN and noted increase in interest and number of references. 61% of the researches was on dependability analysis, followed by risk analysis with 26% and maintenance with 13%.

As mentioned in previous chapters, risk assessment is used to aid decision-making (Modarres et al., 1999). Due to the advantages listed in Section 2.3.4.1, BBNs have been suggested in the literature to improve decision-making processes, which is also important in the risk assessment practices. The main application areas of BBNs in project risk assessment has been identified as; creating a cause and consequence diagram among the risks, obtaining risk probabilities, analyzing how much a specific node is influenced by other nodes by calculating the CPTs among risks and conducting sensitivity analysis to identify major risks which affect project performance (Heckerman, 1997; Lee et al., 2009). The first contributions of BBN in risk analysis were made by Hudson et al. (2002) to assess military risks. Then Nasir et al. (2003) created a model for assessing schedule risks in terms of activity durations interpreted as percentages of most likely durations. Fan and Yuu (2004) proposed a BBN based software project risk assessment process to support decision-making. Their procedure utilized BBNs to analyze risks and generate information to the manager; while the manager may input evidence or decisions to the BBNs for further estimation and prediction. For continuous risk management, they proposed a BBN-based risk management procedure which consisted of; 1) initialization, 2) maintaining project risk profile, 3) performing risk analysis and monitoring, 4) risk treatment stages. Later on, BBN was used in Lee et al. (2009)'s study for large engineering project risk management. It was chosen over influence diagram and cross impact methods, due to its ability to represent detailed relationships and calculate conditional probabilities of risk items.

2.3.5.1. Bayesian Belief Network for Assessing Construction Project Risks

In the literature, only a few researchers attempted to use the Bayesian Belief Network method to investigate the construction risks. Among these; Nasir et al. (2003) proposed the first novel approach to assess delay risks in construction projects. They developed a BBN model named "Evaluating Risk in Construction-Schedule Model (ERIC-S)" for schedule risk analysis to determine the upper and lower activity duration limits based on project characteristics. The model information was provided mostly from experts, together with project reports and literature surveys. The risk variables were classified into ten categories as; environmental, geotechnical, labor, owner, design, area condition, political, contractor, contractor non-labor resources, material. After the model was created it was tested with various cases and the results of the BBN model was then entered to the schedule to be used for Monte Carlo simulation. Luu et al. (2009) also used BBNs for predicting probability of schedule delays in Vietnam construction industry. After they developed a BBN through expert sessions, they identified the least and most important factors causing delays. More recently, BBNs have found its use in safety analysis of Nuclear Power Plants in Kim et al. (2017)'s research.

As also mentioned in Section 2.2.4, utilization of BBN for tunnel risk assessment was introduced in the works of Sousa and Einstein (2012) and Cardenas et al. (2014). In Zhang (2014)'s paper; the aim was to merge BBN and Fuzzy Logic principles in a Fuzzy Bayesian Network (FBN) to provide an alternative construction failure analysis method for tunnel constructions. Tunnel leakage was specifically identified as the risk output. This work is found especially important for this thesis, due to its content related to tunnel projects. Apart from the creation of a BBN model, the novelty came from involving Fuzzy Probability Assessments for determining the conditional probabilities.

Additionally, like Nasir et al. (2003)'s study, Yu et al. (2017) also utilized BBN and Monte Carlo simulation together for assessing schedule risks, but this time for estimating the probability of completing the TBM excavation within a specified duration. Then, Chung et al. (2019) suggested a BBN based cost overrun risk assessment method for TBM tunnel projects. They have identified the risk events for shielded TBM excavation operations. The risk sources were categorized as geological related, design related and construction management related sources. According to Chung et al. (2019), the common methods for risk assessment in TBM tunnel projects that utilize risk registers fail to provide a systematic cause and effect analysis or quantitative analysis of risk factors. Therefore, they have created a BBN for estimating the direct costs of mitigation methods to overcome the risk events. An indirect cost aspect is added consider the stoppage costs accumulated during the interruption of TBM advancement.

In summary, among the many risk assessment methods utilized for tunnel projects, BBN has been proved to be one of the most efficient tools to model complex relations between project parameters and risk factors, thus it has been applied in various tunnel projects. The superiority of the method lies in its ability to express a network of interrelated parameters and risks for probabilistic analysis, to conduct quantitative analysis of dependencies between variables and deal with uncertainties in data. Thus, BBN is selected as the basis of the risk assessment method that is developed in this research.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter will explain the research methodology developed in this thesis. The research process is conducted in collaboration with a real construction company. The research gaps and objectives have been identified according to the findings from the risk assessment practices in real tunnel constructions and literature studies. Therefore, a brief description of the case company is firstly introduced in this chapter.

3.1. CASE COMPANY

This research has been carried out with the collaboration of an international Turkish construction company. The Company is among the largest engineering firms in the country, selected as the top service exporter in technical consultancy field by Turkish Exporters Assembly and is consistently ranked among the top design companies in the Engineering News Record (ENR-225).

As given in the company website, the Company is specialized in design, construction supervision and project management services, operating in 16 countries throughout the world. The type of projects that the Company has been experienced in varies from, transportation; motorways, highways, railways, urban rail transportation, airports, marine structures, bridges, viaducts, environment and infrastructures; transmission lines, pipelines, treatment plants, masterplans to buildings; smart buildings, industrial, education and health facilities, combining all aspects of design and engineering fields.

Case study research has been defined by Yin (1994) as an “empirical inquiry that investigates a circumstance within its real-life context, when the boundaries between this circumstance and context are not clearly evident; and in which multiple sources of evidence are used”. It is a theory building method that helps to describe, understand and predict complex problems (Woodside and Wilson, 2003) through already known evidences. In this research, a case study was conducted in which the role of the Company can be summarized in four major efforts:

- Identification of research gaps: The risk assessment reports from the case study projects of the Company are analyzed by the researcher. These reports correspond to four actually constructed railway system tunnel projects located in Turkey, Qatar and Europe. The case study projects are further summarized in Section 3.1. The main findings obtained from the analysis were; the risk assessment practices in tunnel projects (Section 3.1.2), the improvement areas in these practices (Section 3.1.3), and risk registers for tunnel projects (Appendix-C). The identified research gaps have been shared with the Company professionals and their perspectives have been considered while determining the context of this research.
- Development of the computational model: The risk assessment model developed in this thesis has been established by conducting series of sessions with company experts. Total of 9 sessions were carried out to create the model with the participation of 7 experts (Section 5.2.2) through questionnaires, concept sorting and interviews.
- Conducting validation tests: A testing procedure is carried out for the model and the tool in order to validate the model and test the behavior of the developed tool. The procedure included participation of experts from the tunnel consultancy field due to the necessity to compare the results obtained by utilizing the proposed method with actual tunnel constructions.
- Case study implementation: The developed risk assessment tool is implemented on a real case tunnel project with two experts participated in various stages of the same tunnel construction. This process is carried out to test the applicability of the tool and observe how it enhances the decision support mechanism in delay risk assessment of tunnel projects.

Within this context, the Company has provided risk assessment reports of four different projects that have been implemented in the tunnel construction field. These four projects were conducted in Turkey, Qatar and Europe that has been either designed or consulted by the Company. The risk assessment studies have been carried out by different teams that have participated in each of these relevant projects. In scope of this research, each of these risk assessment reports have been examined by the researcher.

The next sections of this chapter will give brief summary of these four case study projects and the limitations identified in the current practices.

3.1.1. Information on Projects

As mentioned previously, the project risk assessment reports of four tunnel projects have been analyzed by the researcher. Brief summary of these projects are summarized as given below.

Case Study 1: The first project is an underground motorway tunnel project of 14.6 km length that is constructed in Istanbul. Both TBM and NATM were used for constructing the tunnel. Bentonite slurry TBM machines were selected for 3.4 km length underground tunnel section, NATMs were used for tunnel connection sections. Cut and cover tunnel sections were also constructed for rather short distance of 1 km length. The planned motorway tunnel line was planned to carry 100.000 vehicles/day. Anticipated construction duration at time of tender was provided as 55 months. This target schedule assumed a critical path duration of 49 months for the design and construction.

Case Study 2: The second project is the first section of an extensive underground railway tunnel construction project constructed in Istanbul of 13.3 km length. The 9.8 km section is bored with 5 tunnel boring machines and remaining part consists of cut-cover sections. The railway line is planned to carry 75.000 passengers/hour/line and is connected to busy urban railway lines operating for city’s underground metro network.

Case Study 3: The third case study is located in Europe. The metro line consists of approximately 7 km length double railway tunnel construction with 3 EPB TBMs and 7 cut and cover metro stations. The scope includes the connection structures with the city's existing metro line.

Case Study 4: The fourth study is located in Qatar. It is also an underground metro line with a length of 10,5 km with a TBM tunnel section of 9,4 km. The remaining part is composed of NATM tunnels and cut and cover metro stations.

3.1.2. Project Risk Assessment in the Case Studies

As mentioned before, the risk assessment reports of four case study projects summarized in the previous section have been obtained from the Company. These reports include the risk assessment procedures carried out in four major tunneling projects and thus are accepted to provide adequate representation of the risk assessment practices that are carried out in the field. In order to examine the application of risk assessment in tunnel projects, four reports have been examined by the researcher and their deficiencies has been evaluated. The identified key aspects of these works and their limitations have also been discussed with a senior project manager in the Company through an unstructured interview. The risk assessment procedures carried out in the examined project reports are summarized below.

Case Study 1: In the risk assessment work of this project, the aim was; to identify the main cost and schedule risk drivers, to assess the potential risks and their consequences, to evaluate the schedule risk for both earth pressure balance tunnel boring machine (EPBM) and New Austrian Tunnel Method (NATM). The risk of finishing the project within the estimated budget was not considered in the risk assessment. However, the cost impacts of each risk were included in the probability-impact matrices in the analysis section. The process started by forming a workshop group. The participants in the risk workshop identified major cost and schedule drivers from a qualitative perspective. Risks identified during the workshop sessions were recorded on a risk register. Risks were assessed qualitatively as; likelihood of occurrence of risk, potential cost impacts, potential schedule delay. Then a three-dimensional probability impact matrix was formed and rated by the workshop participants. Prioritization of risks in the risk register was based upon the sum of cost and schedule risks. Following this, the project team performed a quantitative risk analysis of the schedule uncertainty surrounding the construction durations for critical and near critical activities with Monte Carlo simulation. The analysis was based upon credible optimistic, most likely and pessimistic tunneling advance rates and other critical path activities. This procedure provided two results; i) identification of the most critical risk factors in terms of cost and schedule risks for TBM and NATM tunnels; ii) identification of the most critical activities in terms of construction schedule risk for TBM tunnels.

Case Study 2: The risk analysis in this case was similar to the first example where; the risk assessment procedure was carried out through an Integrated Risk Management Team (IRM Team). The risks were identified in terms of cost, schedule, safety and quality. This was planned to be achieved by identifying all reasonable risks (referred as hazards) that may occur as a result of a trigger event, minimizing the probability of occurrence of these risk to an acceptable level, mitigating the severity of their consequences should they occur and introducing control measures to assure that these risks are effectively managed. The IRM Team was made up of different task groups specific for each discipline. These task groups determined their own sub-risk registers that are then incorporated by the IRM Team into the overall Risk Register.

- The TBM tunnels: for risks associated with; performance, production, handling and installation of lining segments, TBM design, procurement, delivery, commissioning and operation, tunnel lining stability and serviceability issues, TBM interfaces with other works.
- NATM works: for risks associated with the design, planning and construction of mined tunnel works.
- Cut and Cover works: for risks associated with spatial arrangements and general design and construction of particular stations or other major works, particular

planning and coordination risks for design development and approvals, particular construction risks, station commissioning and operational risks, particular procurement issues for plant and equipment, stability of deep excavations, impacts on existing structures and infrastructures, impacts to community environments, risks associated with design and construction interfaces of adjacent works.

- Railway and Electromechanical works: for risks associated with the provision and installation of railway related equipment, trackwork, trackside and other system-wide services, also railway operational risks such as headway design and control, provision of tunnel niches, sidings, cross passages, crossovers and other track and operational related equipment and facilities.

Risks were ranked in three levels, i.e. low, medium and high similar to the analysis conducted in the first case project. However, differently, each risk factor had to be ranked in four categories; safety, time, quality and cost. The report also included the risk owners, acceptance criteria and actions that are proposed to mitigate the risks.

Case Study 3: The main aim of the risk assessment conducted in this project was to assess the cost overrun risk. Risks of finishing the project within the estimated budget was the principle factor evaluated in the risk assessment. This was planned to be achieved by identifying all reasonable risks that may occur during project execution, predicting the impact of these risks, determining measures for minimizing the impacts or probability of occurrence of these risk to an acceptable level. Similar to the previous cases, the project was divided into sub disciplines while determining the risk factors. These sub disciplines were; TBM works, utilities and traffic, excavation works, concrete works and finishing works, systems and electromechanical works and financial issues. Risks were assessed quantitatively based on the developed risk registers. Each risk factor was assigned with a cost risk unit, quantity, a unit price, effect/change percentage, probability of occurrence percentage that finally lead to “risk cost” of each risk factor. As a result; the total cost risk of each risk factor was determined in the risk register added to obtain the net risk-opportunity amount. The team members compared this total risk amount to the initial contract value and evaluated its acceptability.

Case Study 4: Like in first two studies, in this case study, a qualitative risk assessment procedure has been adopted to assess the risks in tunnel excavations. A risk register has been developed that are grouped under the following categories;

- mechanical or electrical problems on the machine
- human errors during operation of the machine
- geological conditions
- excessive volume losses due to unexpected ground conditions
- risky maneuvers such as cutterhead interventions and crossing of the TBM through excavated stations
- interaction of the tunnel with existing underground structures
- fabrication and installation of the segmental lining
- reduced space between the tunnels (such as at crossovers) or low overburden
- excavation of large cross-section caverns with unfavorable geometry by conventional methods.

The risk factors identified under these categories were listed in a risk register and ranked with a probability-impact matrix system. This matrix used a single scoring system for multi-dimensional impact conditions as depicted in Table 3.1. Therefore, the ranking required more diligence. The summary of the evaluation was ultimately given in the Project Risk Register. This Project Risk Register defined the risk that can affect the successful delivery of the project and certain decisions and actions that can be captured to track and monitor the project risk. These also included certain mitigation measures. Thus, for each risk factor, the risk assessment provided an initial risk assessment and a residual risk assessment result

Table 3.1. *Risk Evaluation Table*

Score	Category	Description		
		Health and safety	Project delay	Economic loss
1	Insignificant	Minor inconvenience, worker can continue work	Delays of up to 8 calendar days	Total loss up to €10.000
2	Considerable	Minor injuries requiring first-aid only	Delays of more than 8 but up to 30 calendar days	Total loss in excess of €10.000 but less than €100.000
3	Serious	Minor injuries requiring medical treatment (down-time)	Delays of more than 30 but up to 90 calendar days	Total loss in excess of €100.000 but less than €1 million
4	Severe	Major injuries, multiple minor injuries requiring medical treatment	Delay of more than 3 month but less than 6 months	Total loss in excess of €1 million but less than but less than €10 million
5	Disastrous	Fatalities, multiple major injuries	Delay of more than 6 months	Total loss in excess of €10 million

3.1.3. Limitations in Current Practices

Main limitations of the risk assessment procedures adopted in practice are identified by the researcher. This has been achieved by reviewing the risk assessment reports of four real case projects of the Company. The reports obtained from the Company has been summarized in the previous section. According to the analyses of these reports, the researcher identified the following aspects and drawbacks of the risk assessment methods applied on tunnel projects. Then, these findings are discussed with a project manager in the Company through an unstructured interview.

Table 3.2. *The Summary of Current Practices on Risk Assessment in Tunnel Projects*

Case Project	Risk Assessment Method	Interrelations between Risks	Mitigation Strategies	Results of the Procedure
1: İstanbul motorway tunnel	Qualitative probability-impact matrix for cost and schedule risks, Quantitative Monte Carlo simulation for schedule risks	Neglected	None	Critical risk factors for cost and time overruns, Critical schedule activities for TBM tunnels
2: İstanbul railway tunnel	Qualitative probability-impact matrix for cost, schedule, safety and quality risks	Neglected	Identified to reduce impact	Critical risk factors for cost, time overruns, safety and quality
3: Europe railway tunnel	Quantitative "risk cost" measurement formula that uses probability of occurrence and cost impact of identified risks	Neglected	None	Net risk-opportunity cost of project, Evaluating acceptability of each risk factor
4: Qatar railway tunnel	Qualitative probability-impact matrix for cost, schedule and safety risks	Neglected	Identified to reduce impact	Critical risk factors cost, time overrun and safety, Critical risk factors after mitigation measures

During the interview, the findings given in Table 3.1 and Table 3.2 are shared and discussed with the Company expert. In light of the expert's judgements on risk assessment methods that are carried out in practice, the given summary table and the evaluations of the researcher, the following limitations has been finally determined.

These findings also indicated the research areas that should be improved, which are further elaborated by the researcher in the next section of this chapter.

First, it is observed that each of these studies used inconsistent terminologies which indicated confusion among the practitioners in terms of risk assessment concepts. Additionally, it was seen that project success criteria have been perceived differently in different projects. Each of these procedures identified different risk categories and eliminated some of the risk factors that resulted with different risk registers in different projects. These limited any benchmarking efforts and sharing best practices for project risk assessment in tunnel constructions.

Commonly in all these practices, risk factors are identified in separate risk clusters ignoring the interdependencies between risk factors. According to Dikmen et al. (2008), these standard methods provide captured knowledge from past projects in terms of single facts; however, they do not provide information on the causes, risk factors and their relations contributing to failure events. This is mainly due to the simplicity of calculation steps in which any complexity involved in considering interdependencies could not be handled by human computational efforts. Secondly, since project risk assessment team members are separated to specific sections and as their experiences and knowledge vary, interpretations of causal relationships possessed limitations.

When it comes to the analysis methods, the probability impact matrices were the common method utilized in all the processes. However, the method only allows subjective judgements recorded by an assigned task group, also criticized by Elmontsri (2014) and manual calculations of the group members through simple equations. It only helps in obtaining assessment results rather than supporting the process itself.

In terms of the results obtained from the risk assessment methods, as also acknowledged by the Company expert, the findings of these processes are poorly incorporated into the project lifecycle. As there is no mechanism controlling the implication of these studies to the operations of the projects, there is the risk of omitting to define effective risk mitigation strategies or even if defined the implementation of these strategies in real life. It was general application that the decisions of the top management shape the strategies of risk assessment procedures in each project. However, as indicated by Cardenas et al. (2014), “the use of risk models that comprehensively integrate risk-related knowledge can prevent failure scenarios not being taken into account.” Thus, there is lack of a structured decision support method to enhance decisions made in case of facing a critical project conditions throughout the life of any tunnel project. There is no tool to evaluate different strategies and their possible implications for the project outcomes.

3.2. KNOWLEDGE GAPS

In this research, a literature review has been carried out by the researcher as summarized in Chapter 2. This literature research also provided examining the studies conducted for assessing risks in tunnel projects and pointing out the knowledge gaps. Additionally, the risk assessment methods applied in current tunnel projects are reviewed with a Company expert as given in Section 3.1.

When the observations obtained from these two sources are combined, the limitations of the methods that have been carried out in practice and in literature are identified for delay risk assessment in tunneling projects. These limitations have been classified in three groups as given in Table 3.3 and further summarized in the following sections; definition difficulties, quantification difficulties and implementation difficulties.

Table 3.3. *Knowledge Gaps*

CLASSIFICATION	KNOWLEDGE GAP
1. Difficulties due to improper definition of risk-related terms	• Lack of a unified risk vocabulary in tunnel risk assessment implementations • Lack of a comprehensive list or network of risk factors including risk sources such as geology, safety, finance, construction
2. Difficulties due to poor quantitative modelling	• Ineffectiveness in defining and assessing causalities between several risk sources in tunnel projects • Lack of quantitative models for handling dependencies and aggregating different risk factors
3. Difficulties in implementing risk assessment methods	• Lack of a comprehensive delay risk assessment methodology and tool for tunnel projects • Negligence of impact of adopting risk mitigation strategies on overall risk.

3.2.1. Difficulties due to Definition

When the reports were examined by the researcher, it was seen that although the analysis in these works have the common purpose of measuring the cost and/or schedule risks, it has been seen that the methodologies had certain deficiencies. The following criticisms were raised to improve these methods;

- "risk factor" and "risk source" definitions were missing in the risk analysis documents,
- terms "risk description", "consequent risk" and "risk item" were used in the risk registers for identifying the project problems,
- the terminology was mixed, confused and used differently in each project, in some cases, same terms were used together without definite separations,

- there is a lack of categorization related to risk sources, such as cost overrun, delay, etc. risks.

In addition, when the literature on tunnel projects were reviewed it was observed that, most of the risk assessment methods in tunnel projects have focused on the measurement of project risks at a certain limited level based on a theoretical model (Kui and Huanhuan, 2013). The problem definition and risk identification were carried out for only a specific source of risk. Due to the nature of tunnel works which are dominated by ground conditions, most of the studies and implications focused on geological factors or safety risks (Sousa and Einstein, 2012; Fouladgara et al., 2012). However, effects of different project participants, design processes, mechanical aspect of tunnels have not been united in one single risk assessment work. This has limited diagnosing the problems in tunnel constructions in terms of delay risks. According to Spackova (2013), these models analyze specific failure mechanisms and do not quantify the overall project risk under extreme conditions.

3.2.2. Difficulties due to Quantification

For decision making, researchers previously recommended clarifying the causal relations between parameters (Tah and Carr, 2000). BBNs have been proven to be invaluable for this, with the ability to handle expert data. However, due to its limited application in the field, the complexity involved during the process, eliciting expert knowledge in numerous sessions and involvement of different parties (Xiao-xuan et al, 2007), this method has not been utilized in any of these case studies. Company experts also noted that participants in these risk assessment works are more accustomed to conventional risk rating structures. Thus, the interrelations between different risk factors, their causal structures and aggregating these factors have been neglected in practice.

3.2.3. Difficulties during Implementation

The literature has introduced various models for assessment of construction project risks. However, when it comes to tunnel projects as also mentioned in 3.2.1, most of the risk assessment literature has focused on geotechnical risks or safety risks. Thus, to implement a risk assessment methodology in real case problems, historic data from various sources should be combined and a comprehensive model as well as a tool should be created for assessing delay risks significant for tunnel projects.

During the analysis of previous risk reports it was further observed that, different methods have been used in practice to evaluate project risks in tunnels. These methods varied from expert interviews and risk impact matrices to Monte Carlo simulations for risk analysis. Although BBN methods are useful in project risk assessment, more simple methods i.e. the probability-impact matrices were preferred in current practices, BBNs has found its place only in theoretical investigations. The risk assessment methods in case studies are rather simple and poor in implementation due to the need for collecting large amounts of data, combining dependencies among risk factors, assessing these risks with comparatively low computational effort, determining how to use the information. in decision making (Sousa and Einstein, 2012; Spackova, 2013). The risk mitigation strategies have also been identified in some of these works however, their impacts on project outcomes have been usually neglected.

There is a lack of common risk rating system, as well as a common quantitative risk assessment process that should be specific for tunneling projects. Additionally, the methods presented so far provided only a qualitative/quantitative risk analysis mechanism and only some included presenting mitigation measures. However, none of these methods helped in assessing risk mitigation strategies and quantitatively evaluating their impact on project outcomes.

3.3. RESEARCH OBJECTIVES

The main aim of this thesis is to develop a methodology to assess delay risks in tunnel projects and create a novel decision-support tool to be used in delay risk assessment of tunnel constructions. This research aim has been identified to overcome some of the limitations in current applications of project risk assessment in tunnel projects given in Section 3.2. In line with this, the following research objectives are defined to provide solutions for the research gaps. These objectives indicate a stepwise description of how they are planned to be achieved;

13. First, a project risk management terminology will be developed. The clarification of terminologies is perceived as the most elemental step before starting to develop a new methodology. Thus, examining the literature on project risk assessment and risk management and case studies conducted in tunnel construction industry, a comprehensive review of project risk management concepts is aimed to be provided for practitioners.
14. Next, it is aimed to develop a comprehensive delay risk taxonomy that includes all risk categories effecting project delay risk in tunnel constructions such as risks caused by sub-contractors, employers, local authorities, ground conditions and properties of the construction area.
15. Third, a computational delay risk assessment model will be created that incorporates various risk categories and different parties involved in the tunneling industry. The current models provide risk assessment of a single risk consequence, however the model developed in this research is aimed to develop a novel BBN based delay risk assessment model which adds perspectives such as “operational risks”, “safety risks” and “slowdown of TBM advance speed”. Through linking different levels, the BBN network will show the hierarchical risk breakdown structure stemming from several risk sources (the root nodes) down to the risk consequences (the leaf nodes) that contribute to project delay risk.
16. Additionally, by defining CPTs and by incorporating the causal relations among risk factors, the developed risk assessment methodology is aimed to consider

interdependencies among the risk factors involved tunnel construction projects, calculates the effect of risk factors on each other and automatically aggregates diverse risk factors to the final project risk.

17. Finally, a decision support tool that can quantify delay and propose effective management strategies will be developed for strategic risk assessment and to support decision-making of experts. It is aimed that a tool will be developed to conduct the developed risk assessment methodology and carry out the risk assessment calculations automatically.

3.4. RESEARCH DESIGN

As explained previously, the current methods have limitations on aggregating and handling dependencies among different risk sources, providing a quantitative risk assessment method and a decision support mechanism. The methods used in current tunneling projects are usually based on a risk scoring system that ignores information about causalities between risk factors (Elmontsri, 2014). The BBN models are regarded as probabilistic, acyclic graphical networks that visually present relationships between variables serving as powerful tools for knowledge representation and reasoning under uncertainties (Heckerman, 1997; Cheng et al., 2002). Therefore, combining BBN and strategic assessment is needed to enable decision makers evaluate the project uncertainties.

The aim of this thesis is to develop a project risk assessment methodology and a decision support tool for tunnel projects by integrating BBNs and strategy assessment to enhance risk assessment practices in tunnel construction projects. This will be accomplished by adopting the project risk assessment framework described by ISO (2009) and strategic risk assessment as described by Frigo and Anderson (2009). BBN developed by Pearl (1982) is taken as the basis for risk analysis. In order to proceed with the research method, a research design is constructed in this section to determine how the previously identified research problems are planned to be handled.

As it is illustrated in Figure 3.1, a sequential method will be implemented including successive data collection and analysis stages. In order to gain insight to the problems of risk assessment practices implemented in these projects, tunnel risk assessment methods have been reviewed from real case projects as well as from literature. First a detailed literature review is conducted to understand the problems in current risk assessment methods in tunnel projects. Then these are combined with the case studies carried out in identified empirical projects. This stage is considered as the preparation stage of the research design. The definition of the problems is previously given in Section 3.2. The research development process is conducted in collaboration with a real construction company. Throughout the research case study and expert knowledge elicitation methods are utilized in various stages.

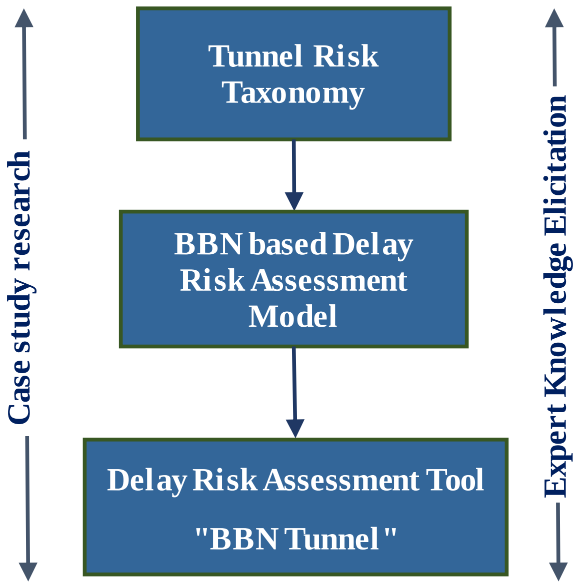


Figure 3.1. The Research Design

The research will be carried out as defined in the following stages.

2. Tunnel Risk Taxonomy: In this stage, two steps will be carried out; i) defining reliable risk assessment concepts, ii) clustering of tunnel projects risk factors leading to delay. First, a comprehensive risk management terminology will be assembled for the development of the overall research methodology. As it is given in Section 3.2.1, definition difficulties are aimed to be overcome through this section. To do this, theoretical and empirical research will be combined. Then, "Categorization" will be carried out using the case study research and interviews with the experts. Here, vulnerability factors and risk factors will be identified by the researcher, then these will be grouped under risk categories based on the risk sources with the experts. Risk clusters will be used to visualize the risk categorization structure, investigate the common triggers, risk events and consequences and determine the risk groups and relevant risk factors. Furthermore, these risk clusters will be the base of capturing complex interactions between risks ranging across different domains in a tunnel project. The results are expected to provide an extensive risk taxonomy for tunnel projects.
3. Computational Model: In this stage, three successive steps will be carried out to create the BBN based delay risk assessment model. The first step is called "risk mapping" in which the risk clusters are combined and converted into a BBN in the software environment. This learning stage of BBN model construction will be carried out via the software tool MSBNx of Microsoft. The software tools used in the research will be described in the following chapters. Further comparison on software developed for BBN applications can be seen in research of Mahjoub and Kalti (2011). After this, the BBN risk assessment model will be constructed in the second step. Expert Knowledge Elicitation (EKE) sessions will be carried out to verify the factors, extend the data and determine the relations between them. Here, all technical aspects of risks constituting the model will be defined and the CPTs between the variables will be determined. This model forms the basis of this research. It will allow the probabilistic calculation of project delay risks and evaluating the effect of different risk factors to the overall project risk. In the third step, the model will undergo several verification and validation tests.

4. The third stage of the research will be carried out for developing the delay risk assessment tool that is aimed according to the research objectives identified in Section 4.4. In order to accomplish this, the outcomes of the previous stage will be used. The results of the tests in stage two, will be evaluated to determine the parameters that will be used in the tool. To introduce the decision support aspect, strategic risk assessment through scenario creation will be carried out. The scenarios created with the experts will be used to make projections about the changes in delay risks. In light of the projections, risk treatment plans and the cost of implicating these plans will be evaluated to find out cost effective risk mitigation strategies. Microsoft Visual Studio will be used to create the interface between the risk assessment model and data input to conduct the analysis. The tool is named as BBN Tunnel, and will be referred as so from this section on. Like the risk assessment model, the developed tool also will be subjected to series of validation and verification stages.

3.5. THE RESEARCH METHODOLOGY

To achieve the objectives of this research, various research methods have been adopted, from expert interviews to case study research. The most important aspect in the methodology is development of this research in collaboration with a highly experienced real construction company. The majority of the data and the expert opinions that are obtained from the research processes are conducted in this Company.

This section of this thesis will give brief information about the steps taken and the findings of the data gathering sessions. In order to accomplish the objectives, the research is conducted in six phases; 1) Research design, 2) Risk taxonomy, 3) Computational model, 4) Decision support tool, 5) Validation of the model and the BBN Tunnel tool, 6) Implementation of real case tunnel projects.

Table 3.4. *The Research Methodology Phases*

PHASE	STEP	METHOD	CHAPTER	OUTPUT
1. Research Design	Theoretical background on tunnel projects and risk assessment methods	Literature Review, Empirical Research	Chapter 2,	Theoretical background on tunnel projects and risk assessment methods
	Research gaps and research objectives	Literature Review, Empirical Research	Chapter 3	Research objectives
	Research Design	Literature Review, Empirical Research	Chapter 3	Research design
	Research methodology	Literature Review, Empirical Research	Chapter 3	Research methodology
2. Risk Taxonomy	Terminology	Literature Review	Chapter 2	Risk vocabulary
	Categorization	Literature Review, Empirical Research, Expert Knowledge	Chapter 4	Delay risk taxonomy
3. Computational Model	Mapping	Expert Knowledge Elicitation, Software Engines	Chapter 5	BBN structure
	Conditional dependencies	Expert Knowledge Elicitation, Software Engines	Chapter 5	BBN based risk assessment model

3. Computational Model (continued)	Assumptions testing	Empirical Research, Expert Knowledge Elicitation, Software Engines	Chapter 5	Assumptions testing
	Sensitivity analysis	Expert Knowledge Elicitation, Software Engines	Chapter 5	Key risk factors
4.BBN Tunnel Tool	Risk assessment process model	Literature Review	Chapter 6	Risk assessment process model
	Strategy assessment & Decision support tool	Expert Knowledge Elicitation, Software Engines	Chapter 6	Mitigation strategies, BBN Tunnel
5.Validation	Validation structure	Literature Review, Software Engines	Chapter 7	Model validation structure
	Validation tests	Literature Review, Expert Knowledge Elicitation, Software Engines	Chapter 7	Test findings
6.Implementation	Case study modeling	Expert Knowledge Elicitation, Software Engines	Chapter 8	Project risk assessment findings
	Real case testing	Expert Knowledge Elicitation, Software Engines	Chapter 8	Real case testing findings

This research proposes a novel delay risk assessment method to implement the project risk assessment in a structured approach specific for tunnel projects. As given in Table 3.4, Phase 1 involves developing the research. This phase is conducted to plan the research process and is utilized to combine the research gaps with the research methodology introduced in this section. Thus, it involves carrying out a literature survey (Chapter 2), determining research objectives and research design (Chapter 3), and creating the research methodology (Chapter 3). The research gaps are identified according to the limitations and problems observed in current practices adopted in tunnel projects as well as the researches on the subject. The next phases of the methodology present the solutions to overcome the research gaps identified in risk assessment methods in tunnel projects. In Phase 2, two steps are carried out for creating the comprehensive risk taxonomy. To overcome the definition difficulties, first terminologies are cleared from an extensive literature review (Chapter 2.3). Then, based on empirical research and review of theoretical background, risk factors are identified, and risk clusters are created for different risk categories. This step is named as “categorization”. After the data validation session with experts, the resultant vulnerability factors, risk factors and risk events provided the aimed comprehensive delay risk taxonomy for tunnel projects (Chapter 4).

In the third phase, the computational risk assessment model is aimed to be developed. Initially, risk clusters are converted into a BBN structure. This stage is named as “mapping”. After that the model for risk analysis is to be developed. Qualitative and quantitative methods have been used together in many research approaches to employ risk assessment in tunnel projects (Yoo et al., 2006; Eskesen et al., 2004; Sturk et al., 1996; Nasir et al., 2003; Luu et al., 2009). At this point the risk assessment model is created in light of the studies of Luu et al. (2009) and Cardenas et al. (2014) who also used BBN as basis. Expert Knowledge Elicitation was the mostly assisted method in this stage. The experts both finalized the BBN model and assigned the conditional probabilities of the various risk relations between the variables. The experts participated in this stage were one of the most experienced specialists in the tunnel practice. This provided gathering valuable expert knowledge in terms of determining relations between risk factors that have been observed through various projects and during TBM operations. The result of this phase presented the BBN based risk assessment model. An assumption testing procedure is also carried out with the experts through the created risk assessment model to observe and test its behavior. Furthermore, sensitivity analysis has been conducted to determine the most influential risk factors and their effects on the project delay risk.

In Phase 4, in light of the results of the previous phase a BBN based risk assessment tool is developed. This starts by developing a risk assessment process model. Then, the risk factors, risk mitigation strategies and the cost of adopting these strategies are determined with the experts. This information is used to develop the tool. The tool is created so that project information can be administered to the model, the risk assessment can be conducted automatically, and decision support outputs can be reviewed and evaluated by any tunnel practitioner with ease. The procedure is described in detail in Chapter 6. In the fifth phase, a validation procedure is created for the research methodology. This procedure is developed so that the data, behavior and accuracy of the risk assessment model and tool would be tested. These tests are further detailed in Chapter 7.

In the final phase, the computational model and the tool are used to implement a completed real case tunnel project. Here, the project is modeled through the BBN Tunnel (Chapter 8). Then the model has undergone series of testing processes to compare the results with the actual project data. As a result of this research, it is aimed to provide an efficient risk assessment tool with decision support mechanism based on the developed BBN based risk assessment model.

To obtain the data and proceed with the successive stages of this research, total of thirteen EKE sessions are undertaken separately with director/manager level professionals to finalize the risk taxonomy, create the BBN model, determine the CPTs, carry out the sensitivity analysis, scenario creation and testing stages.

CHAPTER 4

TUNNEL RISK TAXONOMY

The first section of the research demonstrates creation of the risk taxonomy for tunnel projects. In order to do that, first the risk terminology is summarized as provided in Chapter 2. This has been critical in order to proceed with the terminology that will be used throughout the research beyond this point forward. After that, this chapter will provide the risk and vulnerability parameters and the hierarchical relations among these parameters. In order to accomplish this, the chapter will include creating risk clusters for tunnel projects. Then, the combination of terms, risk parameters and categories will form the risk taxonomy of this research, serve for the risk identification stage of the risk assessment method that is developed.

4.1. RISK CATEGORIZATION

As indicated previously, differences in risk vocabulary in the current risk assessment practices are identified in Section 3.2. and is clarified by providing a comprehensive risk management terminology in Section 2.3. The next stage is comprised of categorization of the risks involved in tunnel projects and finally creating the risk taxonomy. According to Buntine (1996) undirected graphs can be used for problem diagnosis to represent relations between cause and effects. This type of modelling can be achieved by risk clusters.

In this step of the research methodology, the risk clusters are developed to categorize the risks involved in tunnel project. The risk clusters will both provide means to develop these risk categories and to graphically group the related risk factors. For developing the risk clusters, literature survey was the first method utilized. The risk factors that has been identified in current tunnel risk assessment researches has been identified and summarized (Appendix-B).

Then, case study research is carried out by the researcher. Preliminary risk and vulnerability events are gathered for schedule risks by reviewing data in real case tunnel projects. The risk categories, the risk sources and risk factors are identified from the case study risk assessment reports (Appendix-C). Then, to determine the precedence of risk factors from vulnerability factors, these findings are combined with the literature on risk assessment of tunnel construction works.

Separate relations between vulnerability factors and risk events are evaluated for each risk category. Network diagrams of vulnerability factors, risk events and resultant risk factors are determined, their relations leading to deviations from project outcomes are developed. These data are examined by the researcher, to create the risk clusters. The created risk clusters are given in Figures 4.1-4.5. These risk clusters are aimed to help creating the comprehensive risk taxonomy and carry out the risk mapping stage explained in the following chapters. The expert elicitation session given in the following section are conducted to verify and combine these diverse vulnerability factors, train the experts and evaluate the risk classes.

Figure 4.1. Initial Risk Clusters-General

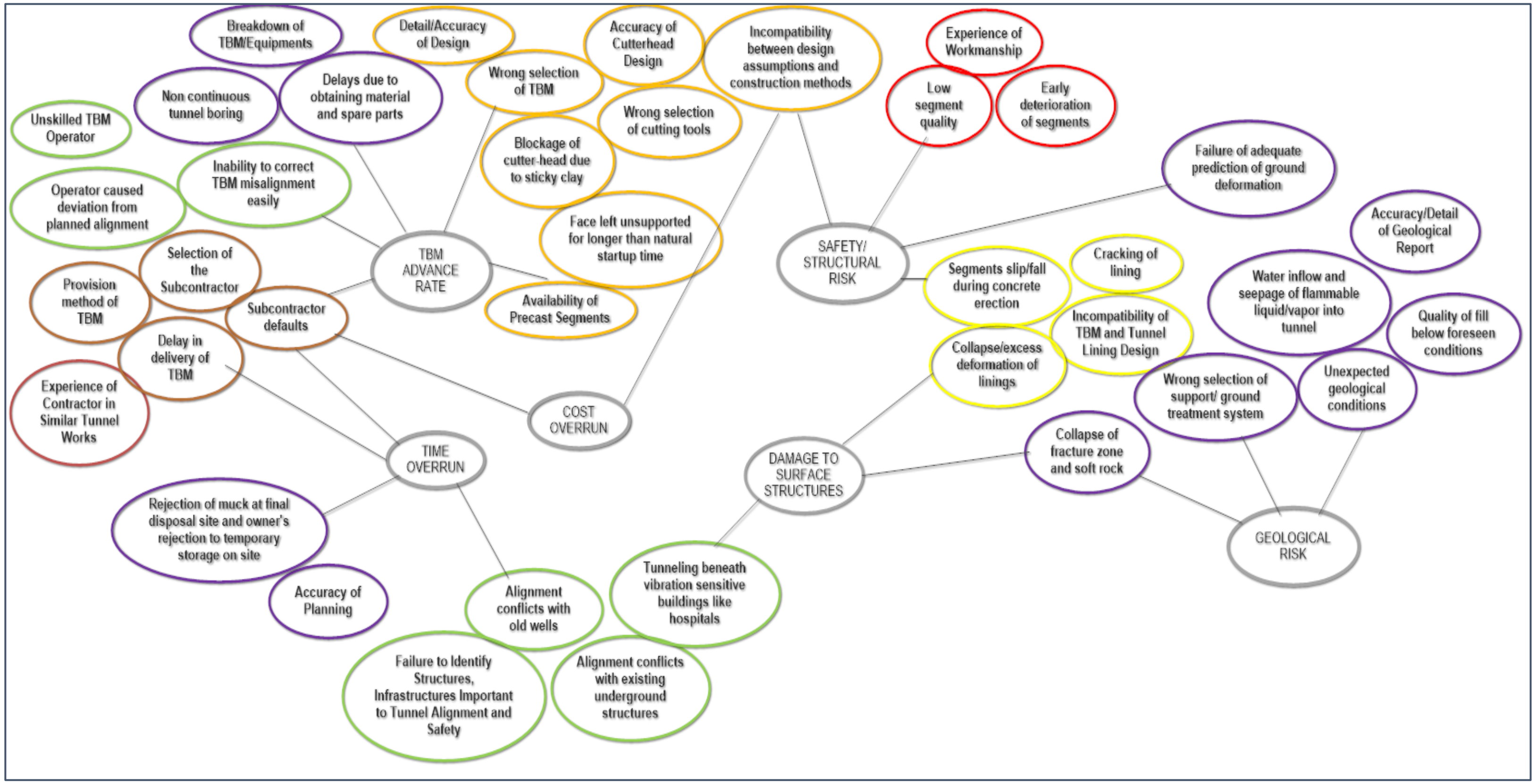


Figure 4.2. Initial Risk Clusters-TBM Advance Rate

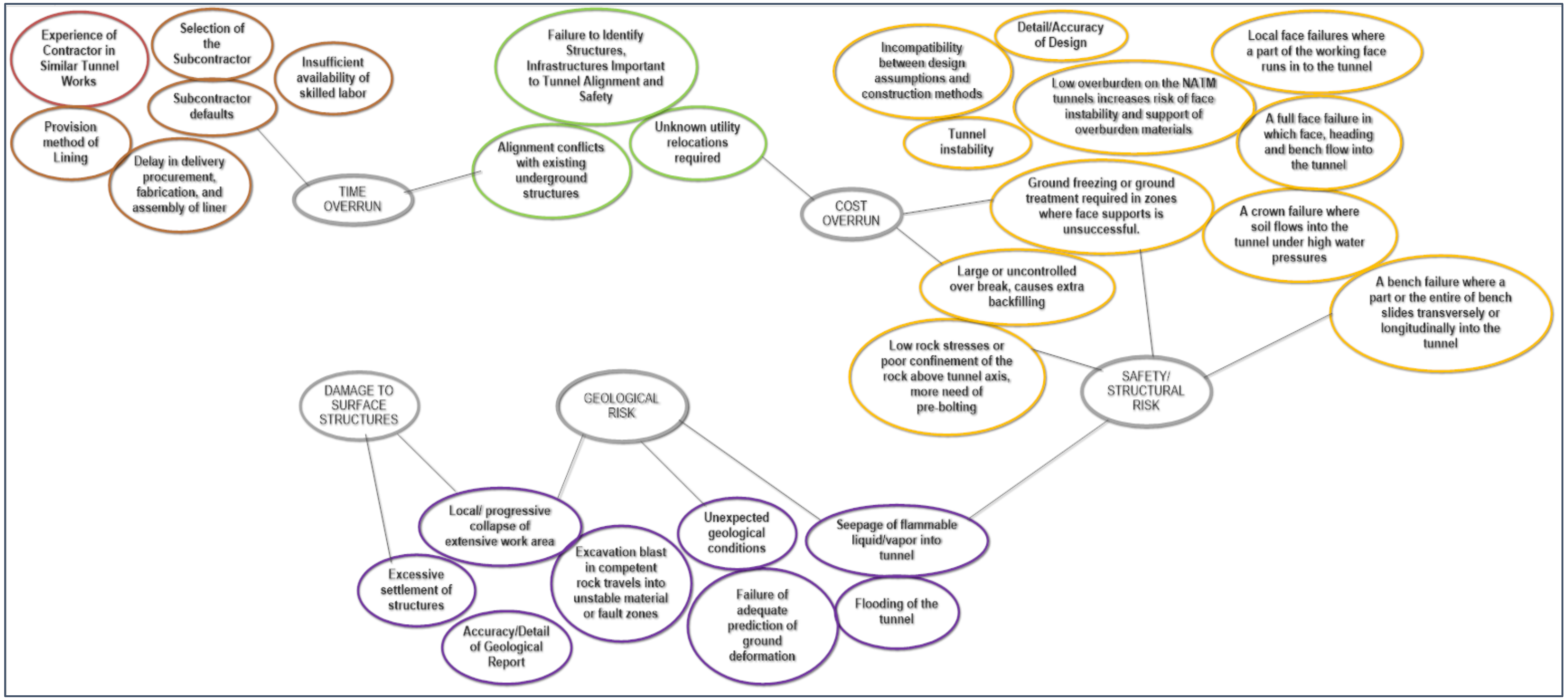


Figure 4.3. Initial Risk Clusters-NATM Construction

Figure 4.4. Initial Risk Clusters-Cut and Cover Sections

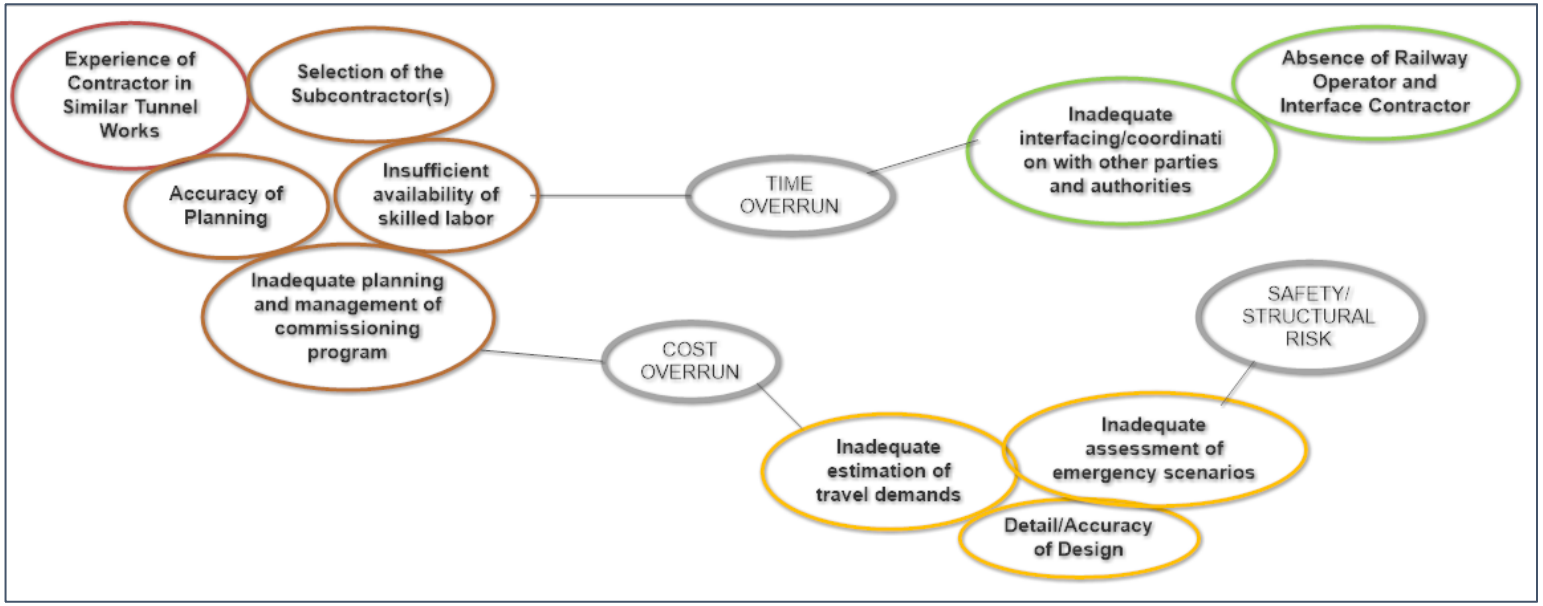


Figure 4.5. Initial Risk Clusters-Electromechanical Systems

4.2. RISK TAXONOMY

To build the delay risk taxonomy, the researcher followed the method suggested by Nickerson et al. (2013). According to Nickerson et al. (2013), taxonomy is the classification of a conceptual knowledge area, which requires determining the characteristics and boundary conditions in order not to expand beyond the subject and overcrowd the problem domain. The characteristic of the subject in this research is identified as tunnel project risks and its boundary condition is limited to the TBM tunnel projects.

In this study, data is gathered through in-depth literature review and case study researches. Therefore, in order to fulfill the principles identified by Nickerson et al. (2013), a risk taxonomy session is planned with the experts (Table 4.1). The previously listed risk factors (Appendix-B and Appendix-C) and risk clusters (Section 4.1), are reviewed through questionnaire's distributed to two experts as Session 1 (Appendix-D). The aim of this process was to train the experts on the model, formally identify and verify the risk factors and categories for tunnel construction delays.

Table 4.1. *Risk Taxonomy Session*

Session 1: Information	
Purpose:	Verifying risk & vulnerability factors, Review and verify Risk Clusters
Type:	Questionnaire
Participants:	2 Project Managers - 10 years civil engineer with tunnel construction consultancy experience
Procedure	
Pre-Session:	Developing the questionnaires with all risk factors gathered for tunnel projects (Appendix-D)

Input:	Questionnaires, Risk Clusters
Methodology:	Overview of data and risk clusters Verification of risk factors and classes Ranking the importance of risk factors with a 1-10 Likert scale
Tools:	Opinion pooling
Output:	Risk factors ranked according to contribution to project delay
Post-Session:	Calculating the weighted importance of risk factors by rating expert judgements according to training and field experience (confidence factors: 0,55 / 0,45) Rewriting and finalizing the risk taxonomy for BBN Tunnel
Anonymity:	The experts' names were shared but their choices are not shared with each other Participants choices are computed in the aggregation process according to unequal weighting calculated according to the level of expertise

The questionnaire has been developed according to the risk clusters created by the researcher. The TBM tunnel risks are elected from these clusters and the questionnaire in Appendix-D is created. Two experts of the Company revised and ranked the most influential sources of risks for tunnel project delays. They noted the negligible risk factors and used a 1-10 Likert scale for the remaining ones. In light of these, the pre-assessed risk factors and risk categories are validated and factors with minor influence on construction delay have been eliminated. The responds of the questionnaires were aggregated using opinion pooling method (Section 5.2.1.2.b). After the results of the questionnaires are obtained from the experts, the researcher discussed about deciding on confidence factor between the participant experts. It was agreed that the expert with a master’s degree in tunnel constructions was rated with 0,55 and the second expert was rated with 0,45 confidence factor. The weighted averages on the responds are calculated using these confidence factors. The most difficult part in this process was the explanation of the reason of the survey. The experts had to make decision on the validity and importance on the risk factors in terms of their contribution to project delay. However, the tendency of concerns involved for tunnel projects was more focused on the safety perspectives. Therefore, the purpose of the study was constantly needed to be reminded to the experts. The final risk factors are summarized in the delay risk taxonomy tables that are given in Appendix-E.

The output of the questionnaire consists of the knowledge and experience of the experts, combined by the risk assessment practices implemented in practice. The output of this stage, delay risk taxonomy, also provided the data for developing the next steps of this research and finally create the BBN based risk assessment model and tool for tunnel projects.

The detailed data provided in the risk taxonomy and the risk clusters are used for the development of the research methodology and in the expert knowledge elicitation sessions. In the next chapter, how this risk taxonomy is utilized to develop the BBN model is explained in detail.

CHAPTER 5

DEVELOPMENT OF THE COMPUTATIONAL MODEL BY EXPERT KNOWLEDGE ELICITATION

This chapter of the dissertation explains the development of the risk assessment model with the Bayesian belief network technique. The procedure consists of three consecutive stages. It starts with a brief description of the procedure on how the previously conducted research is used in this chapter in creating the computational model. Then, a summary on theoretical basis of expert knowledge elicitation methods is given. As mentioned before and as depicted in Figure 3.1, the case study research and expert knowledge elicitation are the backbones of this thesis. Starting with this chapter, expert judgement will be the most utilized method throughout this thesis. Then, the second section of this chapter describes how the risk taxonomy and risk clusters are used and converted to create the BBN based model through mapping, conditional dependency assignment. In the third and final stage, assumptions testing, and sensitivity analysis procedures are explained that will be part of the development process of the risk assessment tool given in Chapter 6 and validation procedures detailed in Chapter 7.

5.1. MODEL DEVELOPMENT PROCESS

After a comprehensive taxonomy is created that complies with the research design created previously (Figure 3.1), the research proceeds with the computational model development phase. As explained in Section 3.3 the main aim of this stage is to develop a BBN based risk assessment model and a computational tool that ultimately contributes to the decision-making processes in risk assessment methodologies. To address the knowledge gaps given in Section 3.2;

- Confusion in risk assessment vocabulary have been cleared by providing a comprehensive risk management terminology (Section 2.3).
- Case study projects and literature review have been used to develop a risk taxonomy that incorporates diverse risk categories. The commonly but separately examined risk sources such as ground conditions and safety are combined to reflect various aspects of delays in tunnel projects (Chapter 4).
- In this chapter, expert knowledge elicitation methods are utilized to convert the risk clusters and risk taxonomy into a BBN model. Then, states and conditional dependency tables will be determined. These are accomplished through various interview sessions with experts from the Company. The process concludes with carrying out testing and sensitivity analysis procedures to observe and verify the behavior of the BBN based risk assessment model.

5.2. EXPERT KNOWLEDGE ELICITATION

After developing the risk taxonomy, expert knowledge elicitation methods are repeatedly utilized in the thesis. These methods are used to develop the risk mapping process and eventually construct the BBN based model. Therefore, this section will review the concepts and theoretical basis on eliciting expert knowledge and how the methods are conducted in this research.

5.2.1. Theoretical Background

Expert knowledge elicitation (EKE) refers to the sub-task of knowledge acquisition (KA) and is broadly defined as "gathering information from an expert" (Shadbolt, 2005). In Garthwaite et. al (cited in Kuhnert et al, 2010) an expert is defined as somebody with knowledge, training and experience about an explicit issue and thus could be consulted in defining or evaluating the subject in question. Therefore, their predictions about the problem is called expert judgment and it is regarded as one of the most dependable sources of information in decision-making.

Expert judgment is widely consulted for problem identification, model development and evaluating results of projects. (Martin et. al, 2012). According to McBride and Burgman (cited in Martin et. al, 2012), the three main types of expertise are substantive referring to knowledge about a discipline, normative referring to accurate definition of judgements in a specific format such as probability values, and adaptive referring to the ability to adapt to new situations. In Ericsson's study (cited in Martin et. al, 2012) it is assumed that a minimum of 10,000 hours of practice is required in order to be able to acquire expert performance. The elicitation process generally includes five steps (Martin et al, 2012);

1. Deciding how information will be used,
2. Determining what to elicit,
3. Designing the process of eliciting judgments,
4. Performing the elicitation, and
5. Translating (i.e. encoding) the elicited information to a model.

The EKE processes usually consists of; a "problem owner" for problem identification and selection of experts, a "facilitator" to handle interactions between experts and the elicitation process itself, an "analyst" for conducting the elicitation procedures such as recording and analyzing the elicited information, and "experts" that indicate judgements about the given topic (Martin et al, 2012).

According to Garthwaite et al. there are certain principles that should be satisfied for accomplishing a good EKE process; the experts should be well-chosen for the subject; the questions should be suitable to advance discussions; statistical coherence should be satisfied; elicitation methods should be flexible and able to fulfill the experts preferences; elicitation should be validated by including more than one expert; the responses should be compared and examined; the analysis should overcome uncertainty in EKE parameters; the elicitation process should be reported in detail

(Hadorn et. al, 2014). Comparison of some of the mostly used EKE methods are given in Table 5.1.

5.2.1.1. Elicitation with Multiple Experts

The subjective expert judgements contain certain level of uncertainties that may be due to lack of knowledge or variations included in its nature (Kuhnert et al, 2010). In these cases, multiple experts can be beneficial for the sake of obtaining more accurate solutions. When including multiple experts, the final purpose is to obtain a single distribution for each variable. This can be achieved by either providing discussion among the experts and then provide a consensus distribution or obtaining separate responses from the experts and then aggregating these into a single variable. Although the process of including multiple experts eliminates the process of trying to extract precise estimates from experts, the "facilitator" in this case is required to synthesize the expert information (Kuhnert et al, 2010).

Table 5.1. *Comparison of EKE Methods (adapted from Proctor, n.d.)*

METHOD	DESCRIPTION	ADVANTAGES	DISADVANTAGES
Interviews	Expert is expected to answer questions about a specific topic	A well-known method Data is Qualitative	Time spending Costly
Scenarios and Critical Incident Reports	Observations are used to construct stories by the expert	Provide insight to problem definition	Reliance on self-reports
Questionnaire	Group of experts respond to questions asked about a given topic	Data is Quantitative Coding is easy	Return rate from experts is low Responses may not reflect the actual reality
Focus Groups	A group of experts discusses, evaluates a specific topic	Make use of various opinions Performance of experts based on given info can be observed	A single expert may dominate the discussion Should not be used for discovering specific problems
Wants and Needs Analysis	Group of experts carry out brainstorming sessions about what is wanted and needed in a system	Make use of various opinions Focus areas and prioritizations can be determined	Responses may not reflect the actual reality
Concept Sorting	Experts determine relationships between a certain set of concepts	Relations between different components can be established, that is particularly helpful for structuring information	The resultant structure may be complex

5.2.1.2. Combining Expert Judgments

As mentioned in the previous section, when using multiple experts in the elicitation process, the resultant information can be gathered through reaching a group consensus or obtained separately and then combined together (Martin et al, 2012). If the second option is used, then the process of combining separate opinions is named as aggregation. The main approaches in this process are named as behavioral, mathematical or combinations of these two approaches (EFSA, 2014).

m. Behavioral Aggregation: In behavioral aggregation, the experts form a group consensus on probability distributions where the elicitor is expected to help the process. The experts can either be expected to reach a common opinion or form a distribution reflecting all answers by weighting different opinions. In this approach, the elicitor is advised to remain impartial and realize and react to biases during the process (EFSA, 2014).

The main disadvantage in this group paneling approach is the high probability of losing complete diversity of opinions, unintentional dominance of a group member or forming subsets among the members. However, in certain cases when the experts strongly object to form any agreement, rather than forcing any agreement more than one probability distribution can be the result or mathematical aggregation can be preferred for proceeding. In these cases, the following method (mathematical aggregation) can be preferred.

n. Mathematical aggregation: Mathematical aggregation consists of separate elicitations where the experts do not interact with each other. After obtaining the results, the individual distributions are combined mathematically (EFSA, 2014). According to Morgan and Henrion (as cited in Martin et al, 2012), this method possesses the advantage of taking into account all different expert judgements and improving the problem analysis value for the decision makers.

The mostly used methods in mathematical aggregation are Opinion pooling and Bayesian methods. In the first method, the expert judgements are aggregated by assigning weights and then taking arithmetic or geometric means (EFSA, 2014). In the Bayesian method, the likelihood functions of each expert judgement are defined by the facilitator, considering different confidence levels. The experts are regarded as independent or dependent, where in the latter case correlation between experts also need to be taken into account. Due to the level of complexity in determining the likelihood functions and the calculation, this method has found only limited use in EKE (EFSA, 2014).

In both of the above described methods, a resultant probability distribution is accomplished by combining different information elicited from experts. In order to do this, confidence levels between experts are advised to be considered. By this way, the advantages and disadvantages of each judgement are combined and thus balanced together. Different weights can be determined between the experts, by the elicitor according to their level of expertise, equal weights can be assigned, or the weights can be determined according to the principles of Cooke's method (EFSA, 2014). Cooke's method determines the weights by comparing the accuracy of responses of experts in a "calibration test" (Cooke 1991; Martin et al, 2012).

According to Martin et al. (2012), among these mathematical methods, the equal-weighted averages can be preferred to combine expert judgements as it provides a simpler calculation procedure with rather accurate results. Similarly, Clemen (as cited in EFSA, 2014) as well as Lin and Cheng (as cited in EFSA, 2014) evaluated that Cooke's combination of expert judgements give only a slight advantage over the equal weighted method. However, according to Cooke, Soll and Larrick and Aspinall (as cited in Martin et al, 2012), in cases where there are definite differences in terms of accuracies between expert judgements, then unequal weighting should rather be preferred to increase the level of accuracy.

o. Mixed techniques: The above-mentioned aggregation methods provide two different approaches to combine expert judgements. Furthermore, Ferrell and Rowe (as cited in EFSA, 2014) presented a combination of behavioral and mathematical aggregation through expert interactions. Other mixed techniques can be named as Delphi method and the Nominal Group Technique (NGT).

In Delphi, a feedback process is carried out to increase the level of accuracy. The procedure starts in separate sessions with each individual expert. This can be conducted in face to face or remote sessions, where the latter option provides a cost and time efficient alternative (Kuhnert et al, 2010). The results are then combined (usually with equal weighting) and shared anonymously between the expert group and the experts are asked to reassess their answers. This iteration is continued until all experts are confident about their responses.

It has been found out that the level of accuracy in this cyclic method tend to increase over rounds as smaller number of experts tend to change their responses in preceding rounds (Rowe and Wright, 1999). Additionally, number of experts that tend to quit in the following round increases as the duration of process increases (EFSA, 2014). In order to overcome these difficulties, EFSA (2014) recommended using smaller group of experts, strong piloting (i.e. choosing more qualified experts), keeping in regular contact and smaller number of questions to be asked.

In Nominal Group Technique, first the experts are allowed to discuss the problem with the presence of the elicitor. Then after the discussion is completed, unlike the previously described behavioral aggregation methods, the experts are requested to provide their opinions about the topic separately. Their answers are then mathematically aggregated to reach a final judgement (usually with equal weighting) (EFSA, 2014).

In certain circumstances, experts cannot reach an agreement such as determining conditional probabilities in scope of this research. There have been two methods that would be conducted to overcome this. According to the theory provided in this section and also identified by Fenton et al. (2006), the theoretical basis of knowledge elicitation and aggregation methods provide the first option. By utilizing mathematical aggregation methods, according to the confidence levels for experts, averaging their opinions can be preferred to reach a result. In BBNs, a second option has been offered by Jensen and Nielsen (2007). Here, an additional parent node is added for each node that the experts disagree in the BBN. In these parent nodes, the expert opinions are introduced as states and thus, their judgements can be aggregated directly into the model itself.

In the next section of this chapter, the summary of the expert elicitation sessions will be provided. As it will be seen, the only aggregation method was utilized in the first session given in Table 4.1. The details of the aggregation method are described in Section 4.2.

5.2.2. Expert Knowledge Elicitation Sessions

Models in general aim to predict the future performance of a new system, a modified system, or an existing system under new conditions. The risk assessment model developed in this chapter aims to provide a novel risk assessment environment to predict delay durations of tunnel projects.

To ensure its accuracy and serve to the intended purpose, the research model is developed with the participation of expert opinions in series of elicitation sessions. Table 5.2 summarizes these sessions that are conducted during development of computational model, BBN Tunnel tool and validation phases.

Table 5.2. *Summary of EKE Sessions*

Phase	Purpose	Session	Chapter	Output
1.Risk Taxonomy	Risk taxonomy	Session 1	Chapter 4	Risk taxonomy
2.Computational Model	Risk mapping	Session 2 and 3	Chapter 5	BBN model
	Computational model	Sessions 4 - 7	Chapter 5	BBN model
	Assumptions testing	Session 8	Chapter 5	Assumptions testing
	Sensitivity analysis and strategy assessment	Session 9	Chapter 5 and Chapter 6	Key risk factors, mitigation strategies
3.Validation and Verification	Model validation	Session 10	Chapter 7	Test findings
	Decision tool validation	Session 11 & 12	Chapter 7	Test findings
4. Case Study Implementation	Case study modeling and strategy testing	Session 13	Chapter 8	Research Findings

Participants and Dimensions of EKE Sessions: Studies on expert knowledge elicitation indicated the importance of involving several experts in the processes. It is suggested that diversity and group assessments improve the precision of results. However, it also brings certain difficulties in analyzing the results. In order to eliminate these difficulties, aggregation measures are reviewed in Section 5.2.1.2. In this study 9 project/division managers from the Company participated in 13 different elicitation sessions. Mostly, face-to-face interviews were conducted with these tunnel construction professionals; managers, experts and engineers who has developed their expertise through working and interacting with different project parties, tunnel construction and contracting firms, tunnel design and construction supervision companies. The background of experts is given in Table 5.3. The sessions are carried out in sub-groups with the participation of at most two experts per session. Involving small group of participants provided less amount of time seeking for reaching a consensus. Additionally, participants from diverse backgrounds and experience in different project positions enabled robustness and success in creation, scenario planning and validation stages.

Sessions Setup: The sessions were focused, structured and duration of each of the 13 sessions ranged between 3 to 5 hours. Prior to the beginning of each session a pre-meeting training is arranged for each of the experts. These trainings took 20-30 minutes depending on the experience of the expert. The content of this process involves providing a brief background on the research purpose, theoretical information on BBNs used for risk assessment, and explanation of the purpose of the session that is being conducted.

Description of EKE Methods utilized: As described in Section 5.2.1, expert knowledge elicitation methods range from brainstorming sessions to focus groups and there are different aggregation methods from Delphi technique, Cooke's method to opinion pooling. Their advantages and disadvantages are given in Table 5.1. In this study questionnaires, interviews, causal mapping and Delphi techniques are used as expert elicitation methods. In session 1, opinion pooling with non-equal weighting is used for aggregation of different results.

As previously referred, Martin et al. (2012) described four roles in eliciting expert knowledge and mentioned that these roles can be combined together. In this study, a single "facilitator" participated in each session having through background in the model, process and the strategies and sufficient knowledge about BBNs. The facilitator who is also the "problem owner" carries out the "analyst" role as well. In order to accomplish good expert knowledge elicitation processes, the facilitator paid strict attention to anonymity of each response, neutrality, conflict handling, process structuring and validation of the responses.

Table 5.3. *Summary of expert knowledge elicitation procedures*

SESSION	PURPOSE	EKE METHOD	DURATION	PARTICIPANTS	TECHNIQUES
1	Risk taxonomy	Questionnaire	-	2 Project Managers 10 years civil engineer with tunnel construction consultancy experience	Opinion Pooling, 1-10 Likert Scale
2-3	Risk mapping	Interview-Concept Sorting	3 hours without break	2 Project Managers 10 years civil engineer with tunnel construction consultancy experience	Interview, Causal mapping, Focus Group
4	Computational model-States	Interview	3 hours without break	Top Management 20 years tunnel construction consultancy experience	Interview, Delphi method, BBN model
5	Computational model-CPTs	Interview	5 hours with one break	Top Management 20 years tunnel construction consultancy experience	Interview, BBN model
6-7	Computational model-CPTs	Interview	5 hours with one break	2 Division Managers: 15 years tunnel construction consultancy/ TBM operation field experience	Interview, Delphi method, BBN model
8	Assumptions testing	Interview	3 hours without break	Division Manager: 20 years tunnel construction TBM operation field experience	Interview, BBN model

9	Sensitivity analysis and strategy assessment	Interview	3 hours without break	Division Manager: 20 years tunnel construction TBM operation field experience	Interview, BBN Tunnel
10	Model validation	Interview	3 hours without break	Division Manager: 20 years tunnel construction TBM operation field experience	Interview, BBN Tunnel
11-12	Decision tool validation	Interview	3 hours without break	Division Manager: 20 years tunnel construction TBM operation field experience	Interview, BBN Tunnel
13	Case study modeling and real case testing	Focus Group, Strategy Reporting	5 hours with one break	2 Project Managers: 10-15 years civil engineer with tunnel construction consultancy experience	Focus group, Strategy report, BBN Tunnel

5.3. RISK MAPPING

The BBN model of this research require transforming the data from risk taxonomy and risk clusters into the BBN. This involves forming risk clusters and creating the BBN model structure. Therefore, after the risk taxonomy is obtained as described in Chapter 4, the following two stage Risk Mapping Procedure (RMP) is developed.

RMP 1. Mapping risk clusters to BBN: In this research, the graphical mapping method developed by Khakzad et al. (2011) is used as basis for transforming the risk clusters into BBN structure. According to this method the following transformation procedure is adopted.

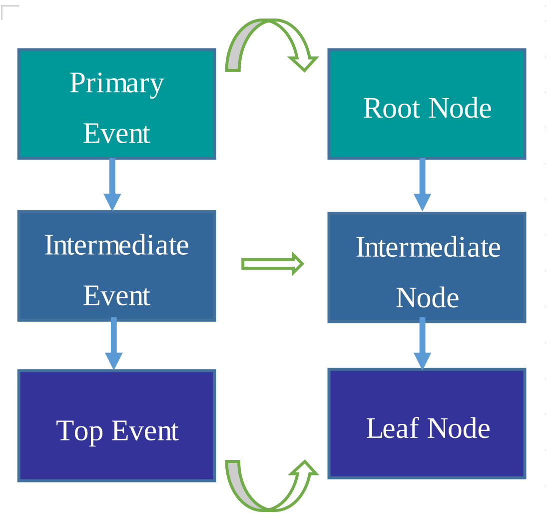


Figure 5.1. Mapping procedure from risk clusters to BBN model (adopted from Khakzad et al., 2011)

Table 5.4. *Risk Mapping Session*

Session 2: Information	
Purpose:	Creating the BBN Model
Type:	Interview
Duration:	3 hours without break
Participants:	2 Project Managers 10 years civil engineer with tunnel construction consultancy experience
Procedure	
Pre-Session:	Development of the mapping procedure
Input:	Mapping procedure diagram, risk clusters, risk taxonomy
Methodology:	Discussion on individual causal maps
Tools:	Concept sorting, causal mapping
Output:	BBN model (preliminary)
Limitations:	Reliance on judgements, Excessive time to make participants familiarize with causal mapping, Excessive time to review and discuss the model, determine the relations
Post-Session:	Modeling the BBN in MSBNx
Anonymity:	The experts' names are shared with each other. However, participants could not see other participants' choices. The company allowed to gather expert data.

In this procedure, primary events, intermediate events and top events of the risk clusters are represented by root nodes, intermediate nodes and leaf nodes in the BBN respectively. According to the scope identified in the risk taxonomy stage, the risk clusters concerning the identified boundary condition, (i.e. TBM tunnel projects) are used for the transformation procedure. The connections are established through the interviews with the experts.

In this context, separate concept sorting sessions are carried out with the same experts that participated in Session 1. Firstly, the mapping procedure in Figure 5.1. is briefly explained and it was expected from the experts to conduct individual causal mapping practices in order to define the hierarchy of events and possible interconnections between these risk events. Each expert created their own causal structures based on model training practice conducted in Session 1. The risk events were converted to root nodes, the risk factors to intermediate nodes and risk consequences to leaf nodes of the BBN model. The final output constitutes the preliminary graphical BBN models.

RMP 2. BBN Model: After the causal mapping stage is concluded with the experts, the researcher modeled the preliminary BBNs on MSBNx. During this process, differences between the experts are identified. Additionally, it is seen that due to the complexity of relations, the computational model becomes highly complex and the visualization capabilities of the software given in Section 5.4 become highly inefficient. Therefore, in order to decrease the dimensions of interdependency relations, divorcing of the parents (described in Section 2.3.4.) method is implemented before this second round of experts' re-evaluation.

Table 5.5. *Risk Mapping Session*

Session 3: Information	
Purpose:	Creating the BBN Model
Type:	Focus Group Interview
Duration:	3 hours without break
Participants:	2 Project Managers 10 years civil engineer with tunnel construction consultancy experience
Procedure	
Pre-Session:	Development of the BBN models in MSBNx
Input:	BBN Model (preliminary)
Methodology:	Overview and finalizing the BBN model
Tools:	Group paneling, MSBNx
Output:	BBN model (final)
Limitations:	Reliance on judgements, Excessive time to review and discuss the model, determine the relations
Post-Session:	Finalizing BBN Model in MSBNx, Translating BBN Model from MSBNx to SAMIAM for testing stages
Anonymity:	The experts' names, ideas and choices could be seen and their choices are shared with each other. The company allowed to gather expert data.

In the second risk mapping session, the created final BBN models on MSBNx are shared with the experts (Table 5.5). Their preliminary models are introduced, and the differences are explained by the researcher. In this regard, each relationship is explained in detail and experts are encouraged to discuss these causalities for reaching the project delay. Based on these final discussions, some additional relations (i.e. arcs in the BBN) are formed and some relations are deleted. This session has been carried out as a focus group interview, where each of the experts could see their models, compare and discuss their proposals and contribute to the most adequate solution for creating the risk breakdown structure of the BBN model. The facilitator remained impartial, realized biases and promoted an equal medium for experts to prevent unintentional dominance of one expert over the other.

The output of this session provided the final BBN Model for proceeding with the next stages (Appendix-F). It includes the risk events (root nodes) and their contributions to the tunnel delay through a set of dependent risk factors (intermediate nodes). The risk events identified in this model are summarized below.

Risk Event (Root Node) 1- Detail of Geotechnical Design: According to the experts, detail of geotechnical design determines the level of survey detail. When the level of detail in geotechnical design decreases it means that ground surveys such as boring logs have not been done as frequent as it should be to determine the exact changes in the soil profile. As TBM advancement is completely carried out below ground, determining the soil conditions as close as possible to the exact situation is crucial. Due to the same reason, the effectiveness of soil improvements that shall be done before TBM tunnel excavation depends on the detail of geotechnical designs. If the geotechnical design is conducted with less precision and higher uncertainties exist at the design stage, the probability of finding explosive gas that was undetected, excessive water leakage into the tunnel and facing unexpected ground conditions increases considerably. Among these major risk factors, secondary factors are also included in the model such as; overbreaks in the rock mass, tunnel instabilities, surface settlements, tunneling below vibration sensitive buildings or wells, segment damages, building rehabilitations for damaged structures, TBM damages and tunnel instabilities. These events would cause decrease in TBM advancement and more severe conditions ultimately result in stoppage of TBM tunneling.

Risk Event (Root Node) 2- Detail of Tunnel Design: In the expert knowledge elicitation sessions, it was determined that precision of tunnel designs determines whether there will be unexpected changes in the alignment designs or not. Designs that do not meet the actual requirements of the construction methodology, needing to change the type of the TBM machine, any requirement to change the tunneling method from TBM to NATM is dependent on the details of the tunnel design. More critically, if the segments that are being produced and placed do not meet the tunnel dimensional requirements and do not fit the tunnel geometry, this means that the designs are critically incorrect. This would certainly result with design revisions, delays and it would be impossible to proceed with the sequential tunneling operations (Section 2.2.3.4) without first changing the projects then resuming the segment production and proceeding with tunneling.

Risk Event (Root Node) 3- Detail of Cutterhead Design: According to the information gathered from the experts, Cutterhead Design is carried out by TBM Machine manufacturers. Thus, its detail level satisfies a certain level of accuracy. However, due to versatility reasons (the same machine may be desired to be used in another project as well), due to contractor's intentional/unintentional limitations (data provided to manufacturer may be limited), the accuracy of design can be comparatively low. In these circumstances, mechanical design revisions can be required during the tunnel boring process. Consecutively, TBM is stopped until adequate mechanic revisions are accomplished. Moreover, when certain unexpected or neglected conditions arise during the operation, cutterdisk can be damaged and tunneling would stop until equipment repairs are concluded

Risk Event (Root Node) 4- Contractor's Experience: In tunneling projects, due to involvement of public funds and highly technical processes that are required during their constructions, main contractors are usually determined through tenders with qualification procedures. The bidders are elected through a screening procedure based on similar works experiences and financial capabilities. Therefore, inexperienced and small contractors are usually eliminated during these procedures. However, even if there is a certain level of expertise, the main contractor could still have the overconfidence in construction methods and thus take unnecessary risks that decrease the advancement speed of the TBM. On the other hand, health and safety precautions would be implemented more effectively by a more experienced contractor, which would considerably decrease the risk of facing damages/loss, causing stoppage of TBM.

Risk Event (Root Node) 5- Place of Construction: According to the experts, construction site for TBM tunnel project is important mainly in terms of segment production areas and site access issues. If tunnel construction is carried out in constrained spaces such as urban areas, it becomes more likely to face unexpected circumstances like infrastructure displacements or historic findings that cause design revisions. Furthermore, in an urban site it becomes more likely to experience delays in getting permits to access site or administrative and expropriation issues that would lead to delays in the operation of tunnel construction works. When it comes to segment production areas, in order to proceed with the sequential construction works, providing a suitable place for storing precast concrete segment becomes important. It is assumed that approximately 70 full rings are required to be stored on a separate and preferably near site area for not delaying the tunneling works. This would require a minimum footprint of approximately 1600 m2 land at the portal side in order to provide an efficient sequential operation process. It was evaluated that provision of such area on site introduces an important operational advantage and lack of such an area would cause additional delays. More critically, TBM type also depends on the place of construction. Among the mostly used TBM types (that will also be used in this research); Slurry and EPB TBMs are preferred more in urban areas whereas Hard rock open type TBMs are used if there is a surface access for operational purposes.

However, experts also noted that although hard rock TBMs provide faster advancement speeds they possess the critical risk of getting stuck in the ground during boring which can cause slowdown of the TBM considerably.

Risk Event (Root Node) 6- Project Duration: It is observed from empirical findings as well as from the expert interview sessions that, construction period of tunneling projects vary between 18 to 36 months. Projects taking less than 18 months and longer than 36 months are considerably unusual due to their feasibilities. The cost of TBM machinery, operation and in general cost of these type of projects generally require projects that would take at least 18 months. This duration highly affects the number of TBMs. Consecutively, addition of a TBM machine abruptly speeds up the tunneling operations. It was also noted that, for projects with longer durations it is usual to be subject to employer’s requirements with respect to speeding up or design revision requests.

Risk Event (Root Node) 7- Experience of Workers: In this research, workmanship is decided to be taken into account in terms of two sub-groups; TBM operator and segment production sub-contractor. When the TBM operator is less experienced, the Contractor always needs to train the operator at the start of the operations which results with delaying the start of tunnel boring. The experience of segment subcontractor on the other hand has a more indirect effect. When the segment subcontractor has limited experience, then loss in quality of segments would contribute to operational delays.

Risk Event (Root Node) 8- Country of Construction: The country of construction is expected to increase the impact of risks. Similar to other construction projects, tunnel constructions carried out in foreign countries influences the occurrence of delays in site access, payments and material supply. These become more critical and causes higher delays when combined with unknown country conditions overseas.

Risk Event (Root Node) 9- TBM Procurement Method: TBM procurement methods in tunnel projects are concluded to have two options; purchased or remodeled. It was suggested by the experts that, project properties and soil conditions are so important and distinctive in tunnel constructions, it is not usually possible to choose among these methods. The previously purchased machine may not be suitable for the ground conditions of the project or the suitable machine may not be available for construction site. However, whenever possible it is common practice that remodeling becomes a more preferred option, as purchasing is usually done from internationally specialized companies and design, mechanical construction and transportation of a new machine delays the start of a TBM tunnel project not to mention the costs involved.

To summarize; the mapping process detailed in this section has translated the risk clusters developed during risk taxonomy stage to a BBN. At the end of this stage, an agreement has been reached by the experts, in terms of determining the model structure. The qualitative section of the BBN, also named as structural learning (Section 2.3.4.) has been accomplished. The final risk assessment model consists of 64 nodes and 99 edges. Both of the experts stated that the resultant model structure (Appendix-F) successfully represents the TBM tunnel construction projects and can respond well to the requirements of contractors in assessing project delays.

5.4. COMPUTATIONAL RISK ASSESSMENT MODEL

The next phase of this research involves utilizing the BBN that is created in the risk mapping stage and convert it into the BBN based risk assessment model for predicting delay risks in tunnel projects. This constitutes the quantitative section of the BBN, called parameter learning (Section 2.3.4.) and represent defining the cause and effect relationships among variables.

In order to do this, firstly BBN software utilized in this research are briefly introduced. Then, the process on how the previously structured model is converted into the quantitative model will be explained. This includes, determining the states of each node and deciding on the probabilistic dependency relations. Thirdly, model assumptions testing and sensitivity analysis processes are explained. The assumptions testing step is carried out to examine the behavior of the model whereas in sensitivity analysis the most important risk factors on project delay are evaluated. These two testing procedures both contributed to the validation purposes and also for the creation of the decision support tool, which will be explained in the following chapters of the thesis.

5.4.1. The Software Architecture for the Model

Due to the complex probabilistic representation and automatic learning structure of BBNs, modern modelling software makes it possible to participate and evaluate the network structure (Mahjoub and Kalti, 2011). As mentioned previously, MSBNx and SAMIAM are preferred in this research for modelling BBNs (Table 5.6).

Table 5.6. *Features of the Software Tools used in the Research*

MSBNx	SAMIAM	DESCRIPTION
Model Creation	Creating Networks	It consists of creating Bayesian networks by introducing nodes, relations and dependencies between variables
Model Evaluation	Inference Engine	It provides manipulating evidence in the model and observing posterior probabilities.
-	Sensitivity Analysis	It provides defining multiple variable constraints and multiple parameter suggestions to control how to adapt these suggested changes. It is important in obtaining key variables in the model.
-	MAP/MPE	It quickly calculates the maximum posterior and most probable explanations in a BBN created.

MSBNx is developed by Adaptive Systems and Interaction Group Microsoft Research and operates on Windows environment. The software creates and evaluates Bayesian

Networks. It uses junction tree algorithm for Bayesian inference and supports integration from other programs and coding languages that make it possible to develop user created components and use them to adapt to specific needs (Kadie et al., 2001). SAMIAM is developed by Automated Reasoning Group at UCLA, which operates on java environment. It has two modes; named as query mode and edit mode. The edit mode (graphical interface) is used to develop the BBN model and assign CPTs. In the query mode, the inference (reasoning) engine is operated. In the query mode, the system does not allow modifications in the graphical network (adding or removing arcs or nodes). It only lets the user enter evidences and observe the behavior of the model. The software includes various implementation algorithms together with an architecture for sensitivity analysis, which makes it superior to many other software packages. These two software are utilized alternatingly in the research, according to the requirements of different research stages and based on their limitations and prevailing properties over one another. The principle features of these tools as provided in the company websites are listed in Table 5.6.

5.4.2. Methodology for the Computational Risk Assessment Model

In order to create the quantitative BBN model, four separate expert interview sessions have been utilized with the presence of the researcher. These sessions aim to determine the probability states, understand the causal relation between these risk events and their interdependency rates. After each session, experts had a re-evaluation period for reviewing their answers and revising if necessary. This process has been carried out because, each session provided input / part of the following session. In the first session as given in Table 5.7, the states of the risk factors have been determined. The expert reviewed the BBN model on MSBNx.

Table 5.7. *State Determination Session*

Session 4: Information	
Purpose:	Determining all states of nodes constituting the BBN Model
Type:	Interview
Duration:	3 hours without break
Participants:	Top Management 20 years tunnel construction consultancy experience
Procedure	
Pre-Session:	Development of a data registry spreadsheet document based on the previously created BBN Model
Input:	BBN model via MSBNx (final), Data registry spreadsheet forms
Methodology:	Overview of BBN model Discussion on individual causal relations and states Overview and finalizing the BBN Model input states
Tools:	Interview, MSBNx
Output:	BBN model
Limitations:	Reliance on judgements, Excessive time to get the experts familiarize with the theory on BBNs, review and discuss the model, determine the relations
Post-Session:	Establishing BBN states in MSBNx, Translating BBN from MSBNx to SAMIAM for testing stages
Anonymity:	The expert's names, ideas and choices could be seen and their choices are shared with the experts in Sessions 5,6,7. The company allowed to gather expert data.

The finalized model was found adequate to represent the Company's tunneling expertise on conducted tunnel projects. Then after understanding the purpose, he determined the states of each node on the BBN. The states are entered into a data registry form, developed by the researcher (Appendix-G).

Table 5.8. *States of the BBN Model*

BBN Node	States
TBM PROCUREMENT	
TBM Procurement Method	Purchase: Acquisition of TBM Machine from the manufacturer, involves design of the machinery by the manufacturing firm Refurbishment: Revision of a previously owned TBM Machine according to the geotechnical conditions of the project
LATE TBM	
Delays in Delivery of TBM Machine/Sub Equipment on Site	Yes No
LATE ASSEMBLY	
Late Assembly of TBM Machinery on Site	Yes No
LATE CUSTOMS	
Delays of TBM Machinery/Sub Equipment in Customs Clearance	Yes No

The findings reflected the knowledge and experience of the expert, gained from previous projects and field practice. These experiences were obtained from diverse project backgrounds and represent his broad thinking perspective as well as the Company's know-how on the subject. Nevertheless, the data obtained from this session is further analyzed and summarized by the researcher. The final material is distributed to the expert for revision and final validation.

At the end of this stage, the contents of the model was finalized with the expert. The expert stated that, the final model (Appendix-F) would successfully reflect tunnel projects comprehensively in terms of the contractors' perspective. An example section of the model is provided in Table 5.9.

After the constructed states are entered into the MSBNx Model, three separate sessions are carried out with different experts in Sessions 5, 6 and 7. Each expert is requested to fill the probabilistic CPT's in light of previously conducted TBM tunnel projects they have managed. Each session has been conducted using the BBN model in MSBNx software.

Before starting the assignments, the sessions started by the researcher/facilitator's briefing on the aim of the session. In these briefings, the concept of BBNs, the general aim of the research, the purpose of the model and the objective of the current session is explained.

Table 5.9. *CPT Assignment Sessions*

Session 5-6-7: Information	
Purpose:	Determining conditional probability values of all nodes constituting the BBN Model
Type:	Interview
Duration:	5 hours with one break for each expert
Participants:	Session 5: Top Management 20 years tunnel construction consultancy experience, Session 6: Division Manager, 15 years tunnel construction consultancy experience, Session 7: Division Manager, 15 years tunnel construction TBM operation field experience
Procedure	
Pre-Session:	Development of the preliminary BBN Model on MSBNx by the researcher
Input:	CPT probabilities via MSBNx
Methodology:	Overview of BBN TUNNEL Model, Discussion on Causal Relations and States of the nodes, Overview and finalizing the BBN Model CPTs
Tools:	Interview, MSBNx
Output:	BBN TUNNEL Model CPTs (final)
Limitations:	Reliance on judgements, Excessive time to get the experts familiarize with the theory on BBNs, review and discuss the model Excessive time for experts to review the interdependencies, especially for intermediate and root nodes with more than three dependent risk factors
Post-Session:	Establishing BBN TUNNEL CPT values in MSBNx, Translating BBN TUNNEL from MSBNx to SAMIAM for testing stages
Anonymity:	Verbal statements were recorded to document the expert opinions and to consult when finalizing the model. The experts names, ideas and choices in sessions 6 and 7 could be seen and their choices are shared with each other. The company allowed to gather expert data.

Session 5 is carried out with a civil engineer in top management position. The expert has 20 years of expertise in tunnel constructions consultancy. He has worked in many metro and tunnel projects during design and construction supervision periods. In scope of this session, first, the expert reviewed the BBN model in MSBNx. After understanding the objective, he has carried out an intense CPT assignment process via the MSBNx model. This process started from the root nodes of the model and proceeded by intermediate and leaf nodes. The software possessed visual limitations for nodes more than three parents, therefore the procedure took almost 5 hours and a break was required during the session. Finally, the expert was satisfied with the dependency assignments and the initial CPT session has been completed. After this session, these values has been shared anonymously among other participants in the following interviews.

In Sessions 6 and 7, two tunnel experts with tunnel consultancy and TBM operations expertize, used the CPT tables from Session 5 as input data. They separately, reviewed these CPT values on the MSBNx and are asked to re-assign their probabilistic values. In this regard, each relationship is explained in detail and experts are encouraged to discuss these causalities for reaching the project delay. The facilitator remained impartial, realized biases and promoted discussion on the parameters to prevent unintentional dominance of the opinion given as input, over the consulted expert opinions.

At the end of these two separate sessions, the two BBN models quantified by the last two expert interviews are reviewed by the researcher. The conflicting node assignments are elected from the model. These assignments are then shared with the experts in a common meeting. In presence of the researcher, the two experts reviewed the conflicting nodes and found a consensus, indicating that the resultant values successfully represent the project wise characteristics and their respective probabilities of TBM type tunnel construction projects. The final CPT Table of a sample intermediate node is provided in Table 5.10.

Table 5.10. *CPT Table of Surface Settlement Node*

Parent Nodes			Child Node	
Survey Detail	**Soil Improvements**	**Overbreak**	**Surface Settlements**	
			Yes	**No**
Detailed	Not effective	Yes	25%	75%
		No	15%	85%
	Effective	Yes	20%	80%
		No	10%	90%
Adequate	Not effective	Yes	30%	70%
		No	20%	80%
	Effective	Yes	25%	75%
		No	15%	85%
Roughly Prepared	Not effective	Yes	40%	60%
		No	30%	70%
	Effective	Yes	35%	65%
		No	25%	75%

After the assignment of CPTs, the quantitative section of the BBN model has been concluded. The BBN model provides probabilistic risk assessment of delay risks in tunnel projects and predict the tunnel delay in terms of project durations. In the next stages of this chapter, mathematical and empirical test conditions are introduced and the behavior of the model is investigated.

5.4.3. Model Assumptions Testing

In order to create and construct the BBN based risk assessment model that answers to the research questions adequately, it was found necessary that the model is subjected to a series of mathematical assumption tests.

As given in section 5.4.1 of this chapter, due to the efficiency in identifying and revising the model probabilities according to desired outputs, SAMIAM software has been used to conduct these model assumption tests. Thus, before initiating the model assumptions testing stage, the BBN model created through various expert elicitation sessions are induced into the SAMIAM software.

After transferring the BBN model to the SAMIAM software, test conditions are developed by the researcher. This is accomplished by defining assumption testing problems for selected control factors under extreme conditions. After that an assumptions testing interview is conducted with a tunnel expert. The session in scope of this stage of research is given in Table 5.11.

In this session, the initial assumption formulas are explained to the expert. These test conditions are then further reviewed and assessed by the tunnel construction expert in the scope of Session 8. The findings reflected the knowledge and experience of the expert gained from previous experience in tunnel construction practices carried out in Turkey, also the diverse and broad thinking perspective of the expert.

Table 5.11. *Model Assumptions Interview*

Session 8: Information	
Purpose:	Model Assumptions Testing Interview
Type:	Interview
Duration:	3 hours without break
Participants:	Division Manager, 20 years tunnel construction TBM operation field experience
Procedure	
Pre-Session:	Transforming the BBN TUNNEL model from MSBNx to SAMIAM Development of the preliminary BBN Model assumption testing formulas
Input:	CPT probabilities via SAMIAM
Methodology:	Overview of BBN based risk assessment model Discussion on model assumption tests list Overview and finalizing the BBN model CPTs
Tools:	Interview, SAMIAM
Output:	Model Assumptions List (final) BBN Model CPTs (final)
Limitations:	Reliance on judgements Excessive time to get the experts familiarize with the theory on BBNs, review and discuss the model
Post-Session:	Finalizing Model Assumptions

The researcher has identified five assumption tests for evaluating the developed BBN model. Among the six assumption tests described below, ACF 3 has been determined by the expert and the remaining assumption test conditions are identified by the researcher, verified by the expert. When these test conditions and formulas are determined, the finalized test conditions are entered into the SAMIAM BBN model through evidences with the expert during the same elicitation. This way, the results are able to be discussed with the experts. The final test conditions, relevant control factors and their model outputs are summarized below.

ACF 1. Duration of Project for TBM Tunnel Delay: As given in section 5.3, TBM tunneling project durations usually vary and take at least 18 months due to high costs and risks involved in these projects. It is foreseen that, as given in Figure 5.2, for smaller projects with durations 18-24 months, if only no other risk events occur "very high delay" is not likely to be encountered.

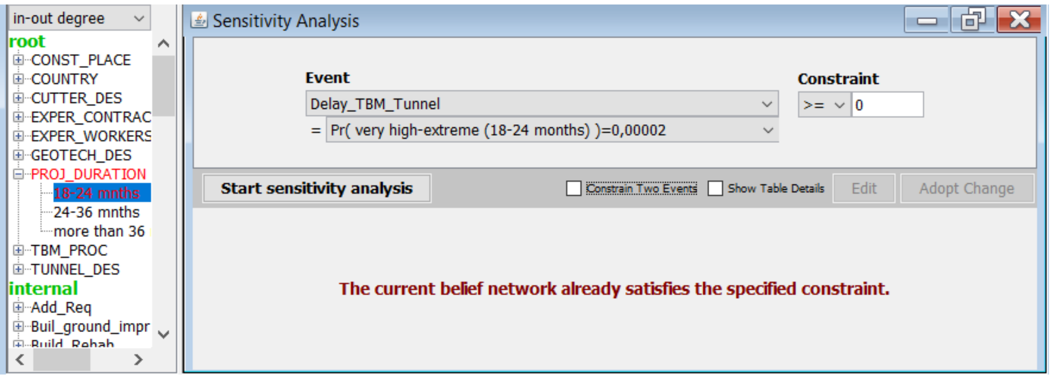


Figure 5.2. SAMIAM BBN model Sensitivity Analysis to Evaluate ACF 1

ACF 2. TBM Type for TBM Stuck: The probability of TBM machine being stuck in EPB and Slurry type are neglected in the study. As it was noted by the experts, the machine can be trapped in soft ground if the TBM machine is hard rock open type. Therefore, for Slurry and EPB type TBMs, the model has P(TBM Stuck: no)=100% probability value (Figure 5.3).

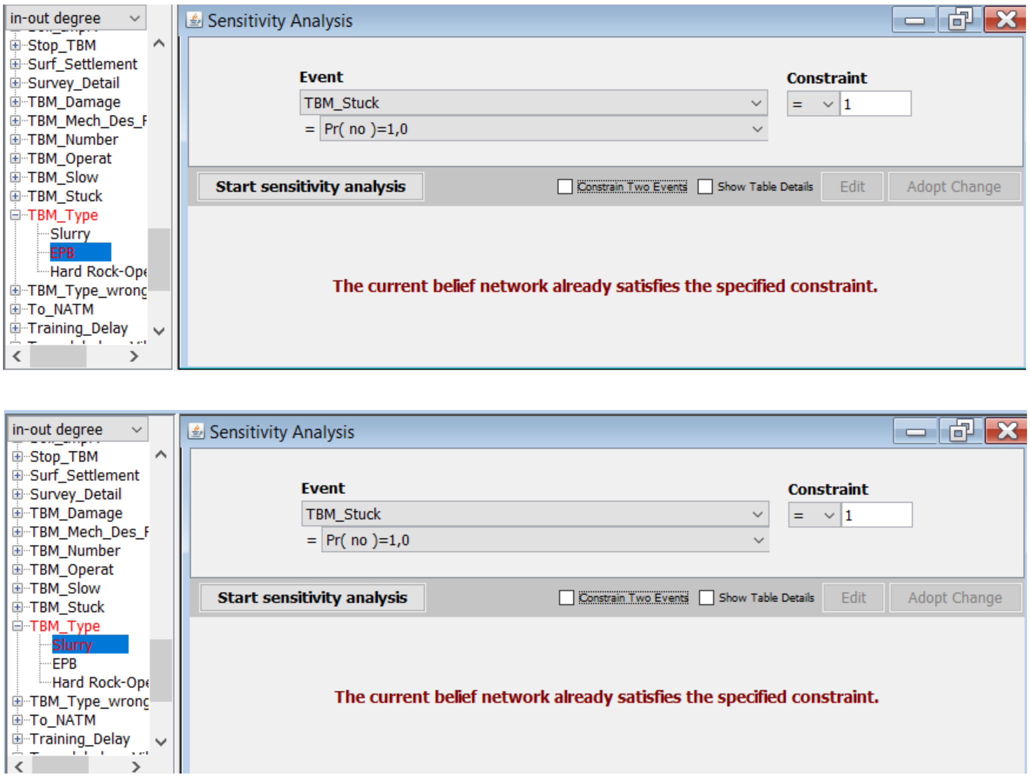


Figure 5.3. SAMIAM BBN model Sensitivity Analysis to Evaluate ACF 2

ACF 3. TBM Stuck for TBM Tunnel Delay: The intermediate node "TBM Stuck" as also given in the previous control factor, is the condition that the TBM Machine becomes trapped into the soil due to meeting unexpected soft soil while boring continues. When this case occurs, it would be required to develop extreme design revisions such as designing a parallel pilot tunnel to rescue the machine or leaving the machine and supplying another TBM instead and revising the tunnel alignment. In any case, if this condition occurs, it is evaluated that the delay of the project is estimated to be at least 6-9 months (i.e. P(Delay:3-4 months\TBM Stuck:yes)=0%). Therefore, the model is revised with the expert in order to achieve this condition.

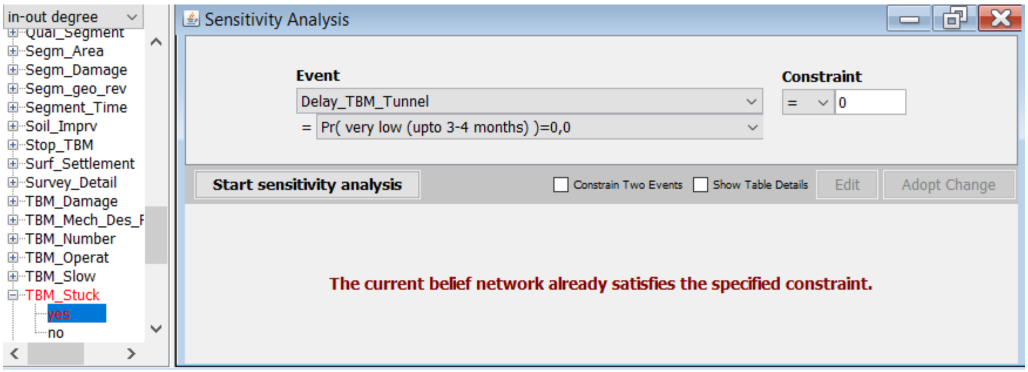


Figure 5.4. SAMIAM BBN model Sensitivity Analysis to Evaluate ACF 3

ACF 4. Leaf Nodes for TBM Tunnel Delay: "TBM Stop" node is one of the leaf nodes that combine and affect the final "TBM Tunnel Delay", which is the main object of the developed BBN model. This node depends on the risk factors; "Health and Safety Issues", "TBM Mechanical Design Revisions", "Injecting the Wells", "Flooding of Tunnel", "Surface Settlements", "Tunnel Instability" as it is depicted in the BBN Model provided in Appendix-F.

According to the previous expert sessions; when the TBM machine stops about 4-6 months due to the above listed risk factors, the project delay is expected to be more than 4 months. Therefore, P(Delay:3-4 months\TBM Stop:4-6 months)=0% (Figure 6.6). Additionally, similar to the same mathematical probability conditions, when the tunnel project starts more than 6 months later, it becomes impossible that the project is finished with very low delay (i.e. delay 3-4 months). This assumption is formulated as follows; P(Delay:3-4 months\Late Start: more than 6 months)=0%.

Similarly, if the operational delays during TBM tunneling sequence reach 4-6 months then the project delay can not be less than 4 months. This is formulated as; P(Delay:3-4 months\Equipment Repair Building Rehab:4-6 months)=0%.

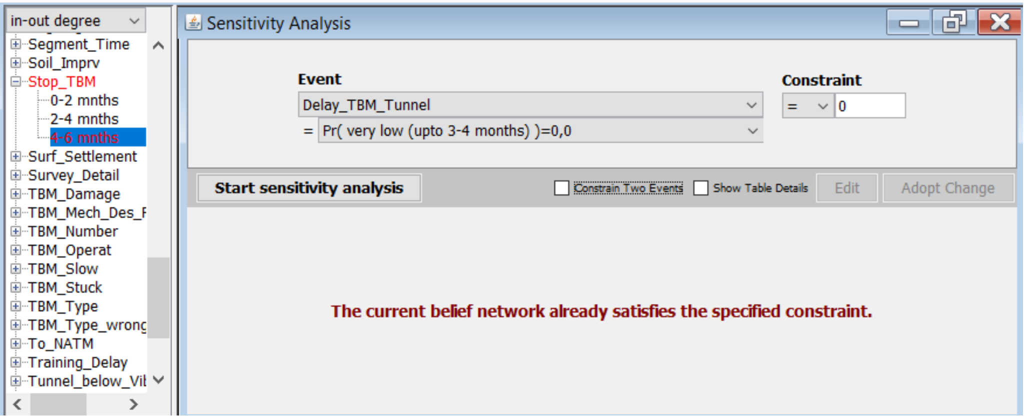


Figure 5.5. SAMIAM BBN model Sensitivity Analysis to Evaluate ACF 4

Lastly, the combination of these cases were also formulated into the model. It is therefore assumed that in case where; the project starts later than 6 months, the operation delays 4-6 months, the TBM stops 4-6 months and equipment/building rehabilitations take 4-6 months, then the tunnel project is expected to be delayed more than 12 months (Figure 5.6).

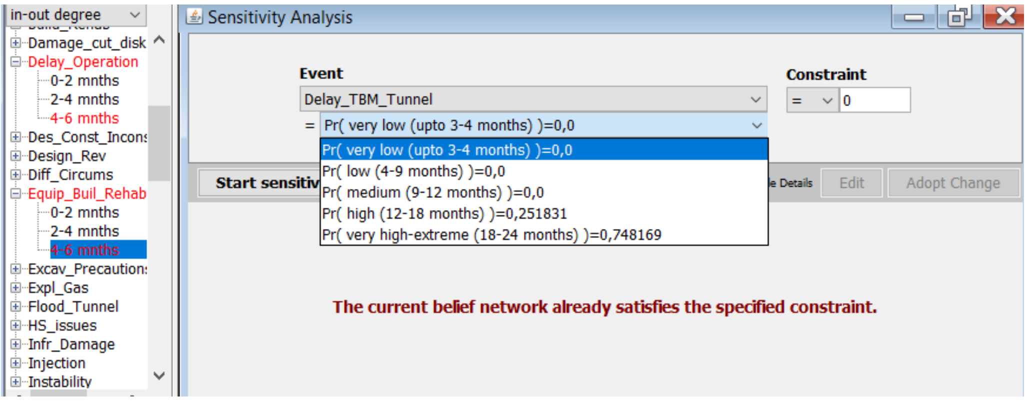


Figure 5.6. SAMIAM BBN model Sensitivity Analysis to Evaluate ACF 4 Combination

ACF 5. Segment Geometry Revision for Design Revisions: The concrete segments that cover the tunnel surface are designed so that they perfectly fit the TBM tunnel cross section. As described in Section 2.2.3.4., the TBM machine pushes itself against these segments to move forward the tunnel face. Therefore, these elements are both crucial in supporting the tunnel lining as well as for proceeding with the boring movement. According to the experts, although it is mostly unlikely that the geometry of these segments do not meet the tunnel geometry requirements, in occurrence of such a case due to detail level of tunnel design or segment production process, comprehensive design revisions would be certainly required (Figure 5.7). The assumption for this case is formulated as; P(Design Rev:major\Segment geometry revision:yes)=100%.

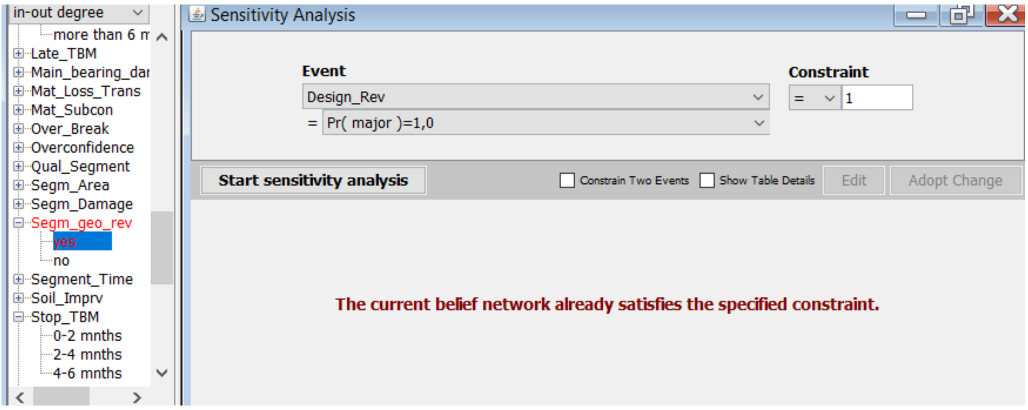


Figure 5.7. SAMIAM BBN model Sensitivity Analysis to Evaluate ACF 5

ACF 6. Project Duration for Number of TBM Machines: In TBM tunnel projects, the tunneling proceeds in a linear operation. The length of the tunnel and number of TBMs determine the duration of the project. The duration is usually fixed by the Employer. As the length is generally adjusted by number of TBM machines and the dismantling/mantling planning of these TBMs, the experts found it adequate that the variables in the model consists of the project durations and number of TBM machines.

Therefore, in this research properties of tunnel projects are described in terms of durations and TBM numbers. It was elicited from the experts that if the project duration is less than two years, most likely the contractor would not use more than six TBM Machines due to costs associated with it. Thus, the following assumption formula is created for the model; P(TBM Number:7-10\Proj. Duration:18-24 months)=0%.

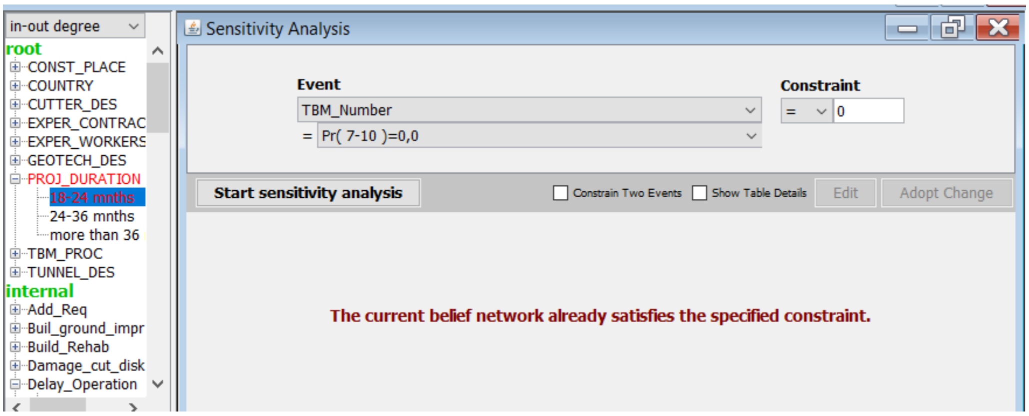


Figure 5.8. SAMIAM BBN model Sensitivity Analysis to Evaluate ACF 6

At the end of this stage, with one modification in the model in ACF 3, the contents of the model has been finalized with the expert. The chosen model was found adequate to represent the Company's tunneling expertise on conducted tunnel projects. The expert stated that the final model would successfully reflect the tunnel projects comprehensively.

5.4.4. Sensitivity Analysis

In the previous section, the model has undergone assumption testing stage with a senior expert and as a result the model is concluded to behave adequately when compared to real case TBM tunnel projects. In this stage of the research in order to proceed with the development of the BBN Tunnel risk assessment tool, a sensitivity analysis is required to be conducted to identify the dominant risk factors controlling the delay risks. Furthermore, according to the results of this analysis, a strategy assessment stage is introduced to the research for accomplishing the decision support purpose of this thesis.

The sensitivity analysis can be broadly described as identification of parameters that impact a model and problem output by changing input conditions (Sargent, 1983). In BBNs this analysis accomplishes understanding the relationships between network parameters and their global behavior in the network (Laskey, 1995). It provides understanding the system behavior, model debugging, identifying variables that do not affect the resultant consequence thus are not required for further analysis and variables that could be considered to be changed to reach a satisfactory global probability distribution (Laskey, 1995; Sterman, 2000).

In light of these, the sensitivity analysis utilized in this section is based on the extreme condition assignments. Each parameter in the model is assigned with range of states from its lowest to highest reasonable values while keeping the remaining variables constant to examine the impact of each risk factor on the final risk consequence. As it was previously determined in Session 4, (Appendix-H), TBM Tunnel Delay node consists of five states; very low (0-4 months), low (4-9 months), medium (9-12 months), high (12-18 months) and very high (18-24 months). In sensitivity parameter analysis, these five states have been centralized using the expected value formula below.

$$E[X] = \sum_{i}^{n} x_i \, . f(x_i)$$

Equation 6.1

Utilizing this formula, a single delay duration has been able to be calculated. Thus, for no-evidence case the tunnel delay duration has been evaluated as follows; P(ML)=0,05x2 + 0,51x6,5 + 0,37x10,5 + 0,07x15 + 0x19,5 = 8,35 months. When each parameter (i.e. node) in the model is assigned with the worst and best case states, an expected value of delay has been calculated for each of these nodes.

The calculation procedure explained here has been carried out by the researcher. For 63 root and intermediate nodes in the BBN model, 2x63 states has been defined and their effect on project delay are examined and compared to the no-evidence case (i.e. most likely case) of the model. The most significant variances as a result of this sensitivity analysis is given in Figure 5.9. The factors with the greatest sensitivity in achieving the targeted project completion dates i.e. nodes significantly effecting the tunnel projects delay are;

- TBM mechanical design review,
- Tunnel flooding,
- Cutterhead design detail,
- Geotechnical design detail,
- TBM damage.

In order to evaluate the sensitivity analysis results and create mitigation strategies, Session 9 is conducted that is summarized in Table 5.12.

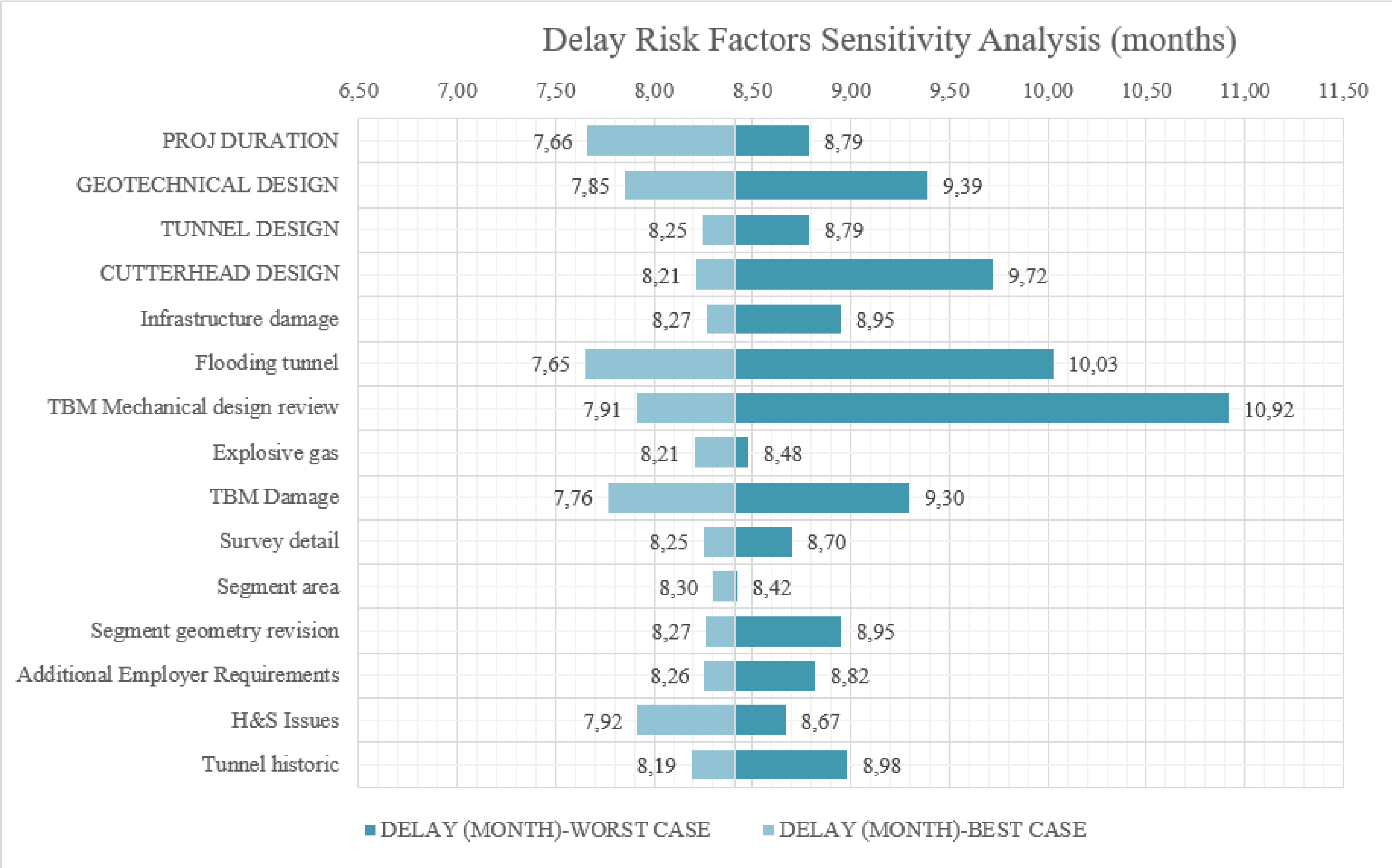


Figure 5.9. Results of the BBN based risk assessment model sensitivity analysis

Table 5.12. *Sensitivity Analysis and Scenario Planning Session*

Session 9: Information	
Purpose:	Determining key risk factors and corresponding mitigation strategies
Type:	Interview
Duration:	3 hours without break
Participants:	Division Manager: 20 years tunnel construction TBM operation field experience
Procedure	
Pre-Session:	Conducting the sensitivity analysis by the researcher, Development of risk mitigation strategies according to sensitivity analysis results by the researcher
Input:	SAMIAM evidences
Methodology:	Discussion on sensitivity analysis results, key risk factors (Chapter 5) Discussing mitigating strategies, their cost consequences (Chapter 6)
Tools:	Interview, SAMIAM
Output:	Sensitivity risk factors, Strategies and their cost impacts
Limitations:	Reliance on expert judgements, Excessive time to get experts familiarize with the theory on sensitivity analysis, Excessive time for experts to review the strategy groupings and determining the costs especially additional consultancy costs were required from payments department
Post-Session:	Calculating grouped strategy costs in terms of percentages of total costs for given projects
Anonymity:	The company allowed to gather expert data. However, the projects of which the cost data is acquired is not permitted to be shared directly as they reflect actual financial and workforce data.

The expert reviewed the results of sensitivity factors and evaluated the following conclusions. Development of risk mitigation strategies are the subject of the next research stage and thus, explained in Chapter 6.

It is seen from the analysis results that, the leaf nodes have more effect on delay duration due to the fact that these nodes are directly included in the CPT of the delay leaf node. Among the leaf nodes, late project start, design review and TBM slow down impact the delay duration more as overcoming these risk factors take longer times and cause increases in project durations. It is evaluated that the critical risk factors affect the project schedules and considering these factors highly increases the probability to reach the planned project completion times.

When intermediate nodes are evaluated, TBM mechanical design reviews and tunnel flooding are the most influential factors and tunnel project delays are mostly sensitive to these two risks. As also stated by Spencer et al. (2009), excessive water inflow could lead to extensive damages to constructions as well as machines leading to high recovery periods to proceed tunneling. However, effect of these intermediate nodes contributes to the project delay risk less than the leaf nodes. Therefore, the measures to decrease their impacts is relatively less critical for the probability of time overruns. When it comes to mechanical revisions, accurate geological information is the key factor for tunnel and mechanical design. Unfortunately, if unexpected soil conditions are faced during excavation that is not considered for the TBM machine being used, then critical conditions like in squeezing conditions would result with requirement to change the cutterhead. Such a revision would therefore require longer durations for stopping boring. In addition, it is seen that cutterhead design detail is more effective on project delay than detail level of geotechnical design. This can be explained based on the impact of their occurrences according to the CPT values given by experts in sessions 5-7. Finally, the expert concluded that these results give adequate representations of TBM type tunnel projects.

As a result of this procedure, the BBN based computational model has been constructed, has satisfied the real case conditions, and the risk factors that influence project delay has been identified with guidance of expert judgments. However, to automate the calculations carried out in the model and to increase the usability of the developed method for a decision maker, it is seen that a tool is necessary especially for promoting the methodology in the tunneling risk assessment practices.

CHAPTER 6

BBN TUNNEL DELAY RISK ASSESSMENT TOOL

In the sixth chapter, the BBN based delay risk assessment tool is developed to help decision-making procedures in the tunnel construction industry. This chapter starts with the description of the processes that are carried out in order to accomplish this and continue with the explanation of stages involved in the process. These stages include carrying out a strategic risk assessment process to create the scenarios for determining risk mitigation strategies, and the development procedure for the tool.

6.1. RISK ASSESSMENT PROCESS MODEL

According to the risk assessment methods that have been carried out in practice and according to the studies that have been examined, the main aim of this thesis is identified as developing a comprehensive methodology and a decision support tool for risk assessment of tunnel projects. In order to accomplish this, firstly it is seen necessary to develop a risk assessment process model, that will identify the steps in the proposed methodology. The decision support tool that is aimed to be created in this chapter will ensure this process model is implemented and the developed method is utilized.

In line with the research design described in Section 3.4 and the literature detailed in Section 2.3, a five-step risk assessment process is developed for this research based on the process utilized by Tah and Carr (2000). The IDEF0 diagram of the risk assessment process as described by Kim and Jang (2002) and Serifi et al. (2009) are illustrated in Figure 6.1.

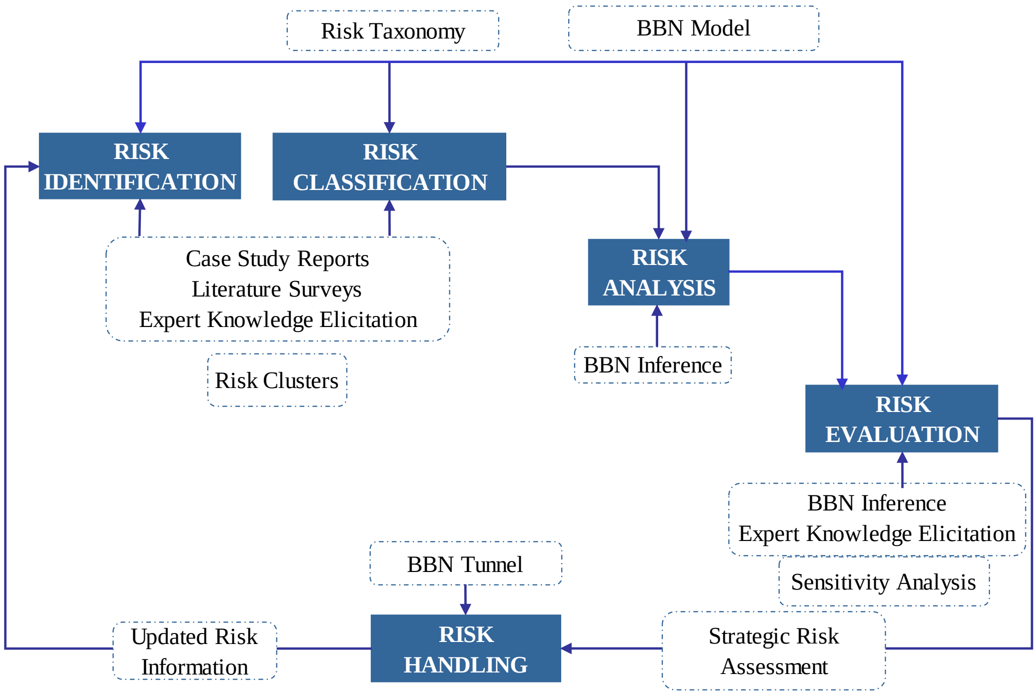


Figure 6.1. IDEF0 Diagram of the Project Risk Assessment Process

The risk assessment process model consists of the following steps; 1) Risk Identification, 2) Risk Classification, 3) Risk Analysis, 4) Risk Evaluation and 5) Risk Handling.

1. Risk Identification: Similar to Tah and Carr (2000) and Dikmen et al. (2008) "risk identification" is the first step in the process. This step constitutes of identification of vulnerability and risk factors which affect the project. In this research various sources (i.e. literature review, case study research, expert knowledge elicitations) are used to identify the risk factors that contribute to delays in tunnel projects.
2. Risk Classification: In the second step, the risks are classified. Among the few studies carried out in risk assessment of tunnel projects, most research has been related to individual risk factors. Therefore, this research used a broad risk classification system for tunnels. In light of the studies carried out in this research

and developed risk clusters, a comprehensive risk taxonomy for tunnel projects is created.

3. Risk Analysis: In this step the quantitative risk analysis is carried out through the BBN Model. In the research methodology developed, this step is accomplished by transforming the risk clusters into a BBN through further EKE sessions are conducted to define the relations and probabilistic data between the variables.
4. Risk Evaluation: In the evaluation step, the most influential factors, their extent to affect the project performance and thus the important risk items that should be controlled are selected. In order to do this, risk items which contribute most to the project outcome are measured by sensitivity analysis. Then, using the BBN Model, evidences are assigned across the computational model and their impacts are evaluated. The results are discussed with the experts. This process provided determining the critical risk factors, and also gave way to develop the decision support tool.
5. Risk Handling: In this step, the risks identified in the evaluation step are dealt with to reduce their impacts on project delay. Thus, after the evaluation step is completed, it becomes necessary to set up necessary procedures to handle the critical risk items and mitigating risks. It was observed that the practitioners would benefit more from the research if it includes a tool that enables data input and analysis steps automatically and also support their strategic decision-making processes in light of the assessment results. This provides carrying out a strategic risk assessment procedure. The BBN Tunnel tool that will be explained in this chapter, provides this by calculating expected delay durations, identifying mitigation strategies and evaluating their impacts on the project outcome in terms of delay and implementation costs.

6.2. PROCESS FOR DEVELOPMENT OF THE RISK ASSESSMENT TOOL

Decision-making is defined as an organization's identification and selection of a solution among alternatives according to the information and problem constraints (Carroll and Johnson, 1990). However, these decisions are usually not structured and rather intuitive (Han and Diekmann, 2001). Until this phase of the research, the stages in the designed research methodology has been followed to create a novel BBN based risk assessment model. In conclusion, it was seen that the tunnel practitioners needed a further effort to utilize the developed model in a more efficient manner, which would also provide them a mechanism to automatize the process, determine the most feasible risk mitigating strategies and contribute to the decision-making process. Therefore, in this phase of the research, to construct the tool in the software environment, the foundation of the tool will be briefly summarized.

The decision support tool development process consists of data input from various phases of the research. First the risk taxonomy is developed in Chapter 4, according to the research conducted through empirical and theoretical basis. During this phase, the risk sources, risk events, risk consequences, their causal relations and interdependency rates have been determined and these are used in creation of the risk clusters. These risk clusters and the identified tunnel risks formed the comprehensive delay risk taxonomy. Secondly, these data are combined with causal mapping procedures, interdependency rates and assumptions testing conditions to create the BBN. This BBN Model forms the center of the research and the base of the decision support tool that is developed in this chapter.

It was evaluated that in order to introduce a decision support perspective in the model, strategies for risk handling and cost of adopting these strategies are needed to be further determined. In order to determine these strategies, the sensitivity analysis results have been selected to be the basis. The risk sources and risk factors that have been identified in Section 5.4.4 indicates the most critical parameters that impact tunnel project delay risk. Therefore, multiple risk mitigating strategies are developed to decrease and minimize this project delay outcome, using these sensitivity results.

In the same expert elicitation interview, Session 9, by evaluating the sensitivity analysis results, these mitigation strategies are created with the experts. The procedure in explained in more detail in Section 6.3.1. Using these data, the computational risk assessment tool is developed by the researcher, via the Visual Studio for running the BBN model in the MSBNx tool. The tool is used for data input, risk assessment and strategy evaluation purposes. It enables automatic calculation of probability of TBM tunnel delay, determining the expected value of project delay in months and observe the changes in these two outputs when set of identified strategies are adopted. The cost outcome of adopting each strategy is also included. In conclusion, the user/decision makers will be able to introduce the project characteristics to the model, carry out a delay risk assessment and obtain the strategic risk assessment results that also enables risk handling.

After briefly summarizing the process that is designed for creation of the tool, the next section will describe development of the strategies that are aimed to support the risk assessment tool and its creation procedure.

6.3. DEVELOPMENT OF THE BBN TUNNEL TOOL FOR DELAY RISK ASSESSMENT OF TUNNEL PROJECTS

In this section, the procedures carried out to create the BBN Tunnel tool will be described in terms of two consecutive stages; carrying out a strategic risk assessment, developing the system of the tool.

6.3.1. Strategic Risk Assessment

According to the risk management framework defined by Cohen and Kunreuther (2007), scenario creation constitutes a useful step for developing risk management strategies. As specified by Miller and Waller (2003), scenarios provide a top-management perspective in terms of problem evaluation and provides involvement of many insights and systems thinking for long-term opportunities. It aims to identify the most influential risk events on project outcomes and develop a range of different cause and effect/risk and response combinations stemming from interconnecting relations (Chapman, 1997; Ackermann et al., 2007). This approach allows analyzing number of different alternative futures to understand which factors contribute more on the outcomes. Thus, based on the sensitivity analysis outputs given in previous chapter, creating scenarios was the method that is adopted for carrying out the strategic risk assessment procedure. This way, it is aimed to incorporate strategic risk assessment and BBN practices.

As described in Section 5.4.4, the sensitivity analysis is carried out by extreme condition assignments. The best and worst cases are examined and the most sensitive risk parameters are identified. According to Spencer et al. (2009) and based on the scenario creation principles of Ackerman et al. (2007), intermediate and root nodes of the sensitive risk parameters are grouped by the researcher to resemble scenarios that would result with delays in tunnel projects. This resulted with forming six scenario groups. If the delay risk is desired to be decreased, it is suggested that these risk factors in each group will have to be assigned from the worst case conditions to their best cases. This would decrease the impact of delay risk in a project, thus provide observing the results in implementation of risk mitigation strategies. Together with the sensitivity analysis results, these scenario groups i.e. strategies are provided as input data for Session 9.

When the experts reviewed the sensitivity analysis results are the strategies developed by the researcher, they agreed on the six strategies to minimize the delay risks in TBM type tunnel projects. However, as mentioned before, these strategies were not seen sufficient by the researcher and the experts to provide a decision support property in the tool. Therefore, the experts are asked to provide the cost of implementing each strategy as well. In order to do that, each risk factor in the strategy groups are evaluated with the expert. In cases the cost data could not be provided by the expert, additional information is obtained from the payments department for consultancy, segment area land acquisition and insurance costs. The final strategies, relevant risk factors and the cost of adopting these strategies are given in Table 6.1.

Table 6.1. *Risk Mitigation Strategies for TBM Tunnel Projects Delay Risk*

Strategy	Risk Factors	Cost of Strategy
Strategy-1 **Geotechnical Design**	Survey Detail, Flooding Tunnel, Explosive Gas, Building Ground Improvements, Cutterdisk Damage, Excavation Precautions, Health and Safety Issues, Main Bearing Damage, TBM Damage, TBM Stuck	3-7% of the Total Tunnel Project
Strategy-2 **Health and Safety Precautions**	Equipment/Building Repairs, Explosive Gas, Flooding Tunnel, Health and Safety Issues, Tunnel Below Sensitive Buildings	5-8% of the Total Tunnel Project
Strategy-3 **Design Revisions**	Additional Requirements, Segment Geometry Revision, Cutterhead Design Detail, Design Construction Inconsistency, Unexpected Alignment Revisions, TBM to NATM, TBM Type Wrong, Excavation Precautions, Geotechnical Design Detail, Survey Detail, TBM Mechanical Design Review, TBM Stuck, Tunnel Design Review, Unexpected Ground Conditions	5-10% of the Total Tunnel Project
Strategy-4 **TBM Advancement**	Infrastructure Damage, TBM Stuck, Building Ground Improvements, Excavation Precautions, Wrong Advance Speed, Delay Operations	8-12% of the Total Tunnel Project

Strategy-5 **Partial Control**	Cutterhead Design, Design Construction Inconsistency, Design Review, Excavation Precautions, Geotechnical Design Detail, Survey Detail, TBM Mechanical Design Review, TBM Stuck, Tunnel Design Detail, Unexpected Ground Conditions, Explosive Gas, Flooding Tunnel, HS Issues, Overconfidence	12-18% of the Total Tunnel Project
Strategy-6 **Full Control**	Cutterhead Design, Equipment Repair Building Rehab, Explosive Gas, Flooding Tunnel, HS Issues, Geotechnical Design Detail, Infrastructure Damage, Late Customs, Late Material, Late TBM, Material Loss Transport, Quality Segments, Segment Time, Segment Area, Soil Improvements, Survey Detail, TBM Mechanical Design Review, TBM Number, TBM Stuck, Tunnel Design Detail, Training Delay, Unexpected Ground Conditions, Wrong Advance Speed	15-38% of the Total Tunnel Project

The first strategy promotes that geotechnical design level can be improved by; conducting more detailed ground surveys (i.e. increasing the number of boring logs along the tunnel alignment by decreasing the distances between logs), additional horizontal drilling equipment, minimizing any chance of unexpected ground conditions, adding water removal measures such as pumping, including gas detection systems, having detailed excavation-support system designs, insurances, providing a comprehensive spare parts stock and specialists for their implementation.

In the second strategy, health and safety precautions are aimed to be increased by having detailed excavation-support system designs and thus preventing any sudden collapse of surrounding structures, adding water removal measures such as pumping, including gas detection systems, insurance precautions, having contingencies for additional renovation costs.

For the third mitigation strategy, the design revisions are aimed to be minimized. This is planned to be achieved by limiting additional employer demands through contract conditions, having additional experts consulting during segment and tunnel geometry design stages, providing a comprehensive spare parts stock and specialists for their implementation, obtaining consultancy for coordination between design-construction operations. Additionally, expertise for gathering data about the alignment prior to construction, additional geotechnical design consultancy for detailed tunnel design, consultancy for determining type of TBM during the manufacturing process, having detailed excavation-support system designs, conducting more detailed ground surveys (i.e. increasing the number of boring logs along the tunnel alignment by decreasing the distances between logs), additional horizontal drilling equipment, minimizing any chance of unexpected ground conditions are included to minimize the design revisions.

In the fourth strategy, TBM advancement is aimed to fulfill the expected average speed by preventing infrastructure damages by additional tunnel displacement sensors and horizontal drilling equipment, consultancy for determining type of TBM during the manufacturing process, having detailed excavation-support system designs, conducting more detailed ground surveys (i.e. increasing the number of boring logs along the tunnel alignment by decreasing the distances between logs), providing adequate segment storage area, providing consultancy services for segment production, having contingencies for transportation losses, training the TBM personnel by the manufacturer during the manufacturing process, employment of experienced TBM operator during the construction.

For strategy five, a partial control mechanism is developed to decrease the delay durations in a more limited perspective compared to full control. In this respect, cutterhead design is aimed to be improved by more detailed customization in the TBM manufacturing process, additional geotechnical design consultancy for detailed tunnel design. In addition to these, obtaining consultancy for coordination between design-construction operations, having detailed excavation-support system designs, conducting more detailed ground surveys (i.e. increasing the number of boring logs along the tunnel alignment by decreasing the distances between logs), additional horizontal drilling equipment, minimizing any chance of unexpected ground conditions, adding water removal measures such as pumping, including gas detection systems, insurances, having contingencies for additional renovation costs are planned to be implemented in scope of this scenario.

In the last strategy, full control of tunnel construction is intended to be achieved through; a more detailed customization in the TBM manufacturing process, additional geotechnical design consultancy for detailed tunnel design, obtaining consultancy for coordination between design-construction operations, having detailed excavation-support system designs, conducting more detailed ground surveys (i.e. increasing the number of boring logs along the tunnel alignment by decreasing the distances between logs), additional horizontal drilling equipment, minimizing any chance of unexpected ground conditions, adding water removal measures such as pumping, including gas detection systems, insurances, having contingencies for additional renovation costs. In terms of operational perspective, this strategy also involves providing adequate segment storage area, providing consultancy services for segment production, having contingencies for transportation losses, supply of an additional TBM, training the TBM personnel by the manufacturer during the manufacturing process, employment of experienced TBM operator during the construction.

After creating these six strategies, at the end of Session 9, the researcher gathered the cost data from the expert. The expert has provided these costs according to a metro tunnel construction project that is being implemented. Therefore, the data provides actual and up-to-date costs. However, it was noted that these values are based on company specific data and provide guidance rather than exact cost impacts on projects. Thus, the researcher suggested calculating percentages of these costs in relation with the total budget of the tunnel project. These percentages are given in 6.3.4.

6.3.2. System Development

The decision support tool developed in this thesis aims to provide a straightforward risk assessment mechanism, a brief summary of risk analysis results that takes into account the interdependencies between various risk parameters, strategic risk assessment and a risk handling aspect by offering different risk mitigation options. The following process diagram has been developed to summarize the system (Figure 6.2).

As depicted in Figure 6.2, the data processing of the tool is carried out with the interaction of two systems; the user interacting system, and the interface that runs the BBN model and delivers its results to the user (i.e. tool). In other words, the interface runs the BBN model in the MSBNx software and reports the results.

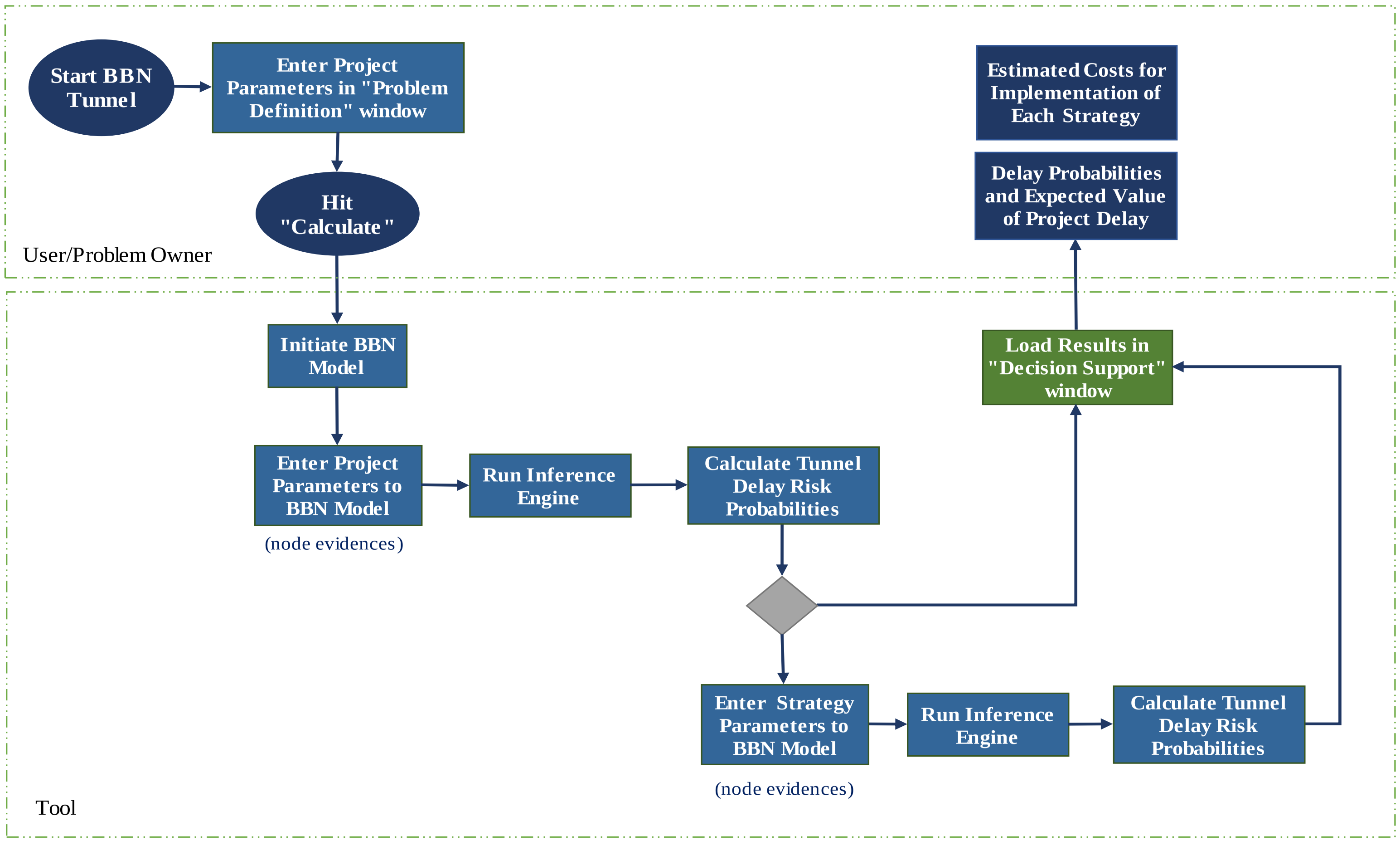


Figure 6.2. Process Flow Diagram of the BBN Tunnel Decision Support Tool

In line with the process flow diagram, the system of the developed tool consists of two agents that are named as the “problem definition” agent and the “decision support” agent. As the names imply, problem definition agent provides the user/problem owner to enter data that reflects the properties of the tunnel project. Whereas in decision support agent, the results of the strategic risk assessment procedure are summarized. The detailed explanations of these two agents are provided in the next sections of this chapter.

When the user/problem owner enters information about the project into BBN Tunnel, the tool carries out the risk assessment process in two parallel operations. In the first operation, Bayesian risk analysis is carried out through the developed BBN model for delay prediction. After the output of project delay is retrieved from the model, a second run in the same model is carried out. In this second run, six different strategies are assigned to the BBN model simultaneously. In this step, the tool overwrites the evidences entered in the first operation, according to the strategies developed in the strategic risk assessment step (Section 6.3.1). The results are reported based on the output of the final leaf node “TBM tunnel delay” and the expected values calculated in terms of delay durations (Section 5.4.4). These also include, the cost impacts of strategy implementations. Based on these, the decision makers would see how much delay their project is expected to face, evaluate cost and time impacts of different strategies and make more feasible decisions.

6.3.3. Problem Definition Agent

As mentioned before, the BBN based delay risk assessment model is created in the MSBNx software. In the main application window, the qualitative part of BBN is created by building the nodes, clusters and arcs. The dependency assignments are carried out in the model diagram window by entering the CPTs of each node. This section can also be used to evaluate the extreme condition testing by entering evidences to a desired node. This property has been used in many of the validation tests that are detailed in Chapter 7. The BBN Tool on the other hand has been developed via the Microsoft Visual Studio software. It is assisted to enable activating the BBN Model, running the analysis and retrieving the results. This is aimed to provide a decision support mechanism for decision makers, by solely assigning project properties to the tool without modifying the empirically validated BBN based model, and obtaining risk assessment results as well as mitigation strategy options.

As seen from Figure 6.3 and Figure 6.4, the main BBN Tunnel tool user interface consists of two windows for data input and output purposes. The left side of the user interface screen, named as the "problem definition" window, provides the data input section. Here, a set of input parameters are listed. In light of the sensitivity analysis that was detailed in Chapter 5, total of 20 parameters are needed to be entered into the model. The user/decision maker defines the properties of tunnel project by selecting the states from the list of dropdown boxes.

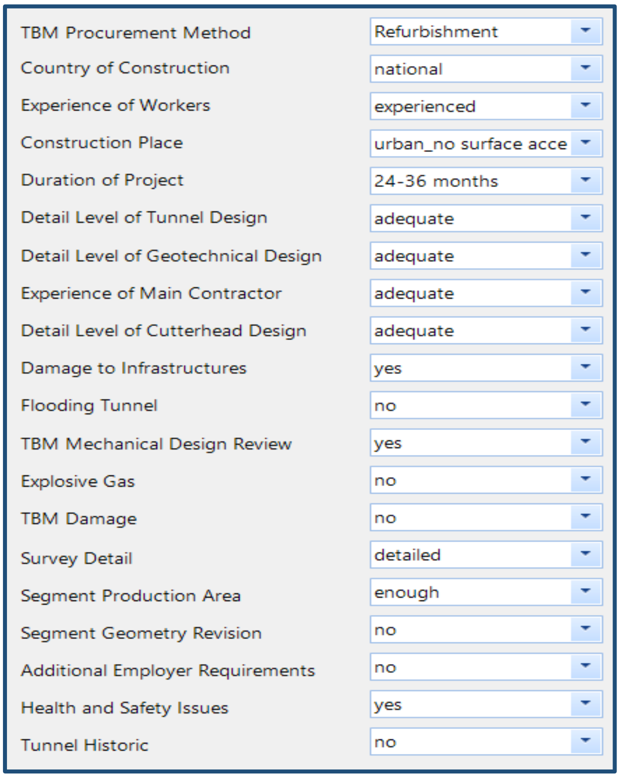


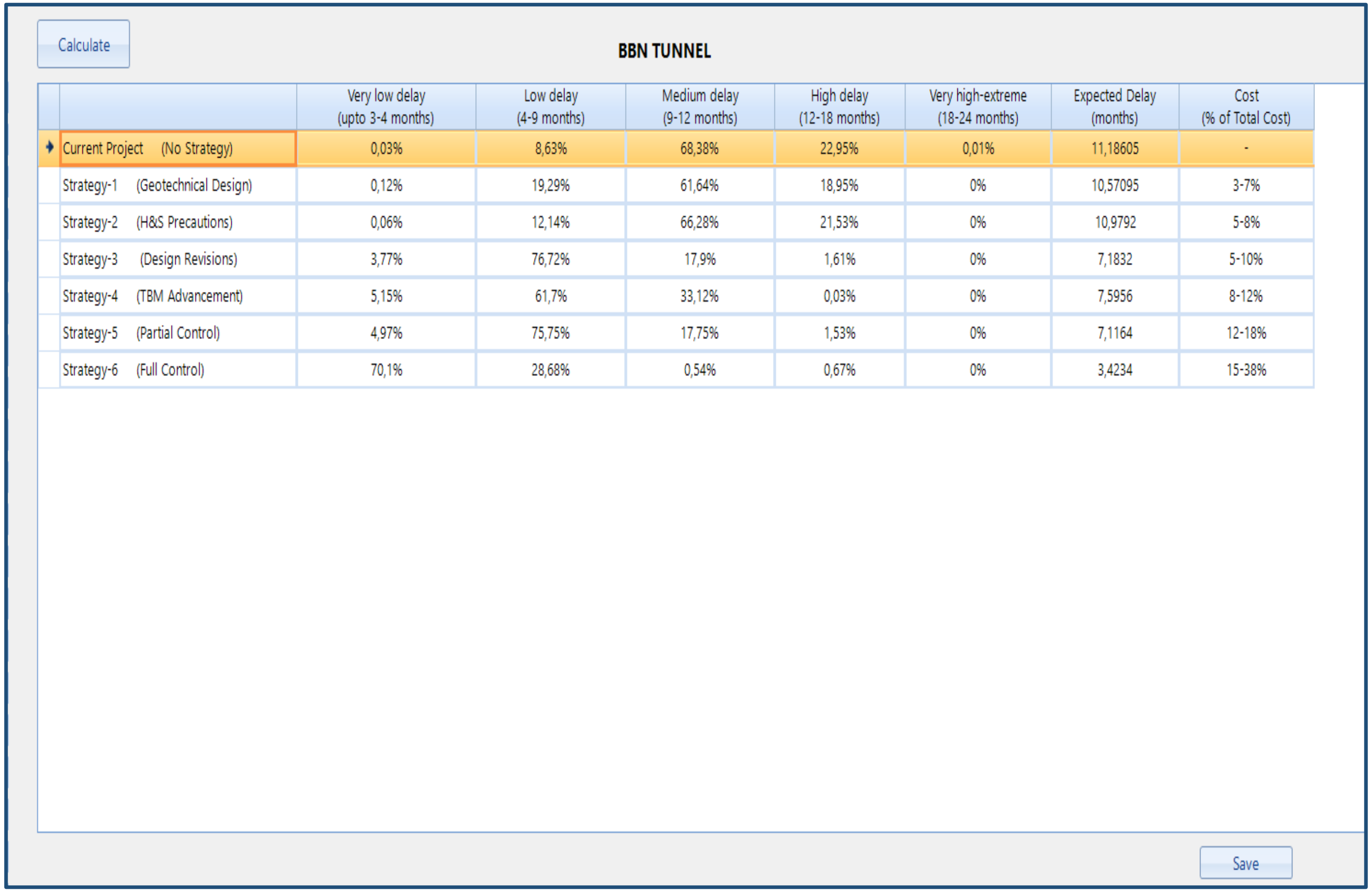
Figure 6.3. BBN Tunnel "Problem Definition" Agent

The process described here, enables identifying the input parameters to define the tunnel project into the BBN model. In the next section, the strategic risk assessment process accomplished by the tool will be described.

6.3.4. Decision Support Agent

The measurement of project success is difficult because it may change during the course of the project, and many stakeholders have different criteria to evaluate it. However, project success criteria are generally measured by time overrun, cost overrun, and technical performance (Baccarini and Archer, 2001; Williams, 1993). The agent described in this section, principally aim to measure project success and decision support by providing strategies to overcome delay risk and evaluating their costs.

In order to accomplish this, an interface has been created by Visual Studio and the ActiveX DLL component of the MSBNx software. A section of the programming code is provided in Appendix-I. When the user hits the “calculate” button, BBN Tunnel tool inputs the selections made in the “problem definition” agent, to the BBN model by assigning them as evidences to the relevant nodes. Then, the BBN model automatically carries out the risk analysis. The result of this risk analysis is read from the “TBM tunnel delay” leaf node and reported in the “decision support” agent of the tool. To provide a more clear indication of delay amount, expected value of delay is calculated, according to the formula given in Section 6.4.4. and is reported as well. This procedure provides the output data of the defined tunnel project and is named as “current project” (Figure 6.4). As it can be seen, probability of each state determined in the leaf node, is given in percentages. Additionally, an expected delay duration is provided to the decision makers in months.



	Very low delay (upto 3-4 months)	Low delay (4-9 months)	Medium delay (9-12 months)	High delay (12-18 months)	Very high-extreme (18-24 months)	Expected Delay (months)	Cost (% of Total Cost)
Current Project (No Strategy)	0,03%	8,63%	68,38%	22,95%	0,01%	11,18605	-
Strategy-1 (Geotechnical Design)	0,12%	19,29%	61,64%	18,95%	0%	10,57095	3-7%
Strategy-2 (H&S Precautions)	0,06%	12,14%	66,28%	21,53%	0%	10,9792	5-8%
Strategy-3 (Design Revisions)	3,77%	76,72%	17,9%	1,61%	0%	7,1832	5-10%
Strategy-4 (TBM Advancement)	5,15%	61,7%	33,12%	0,03%	0%	7,5956	8-12%
Strategy-5 (Partial Control)	4,97%	75,75%	17,75%	1,53%	0%	7,1164	12-18%
Strategy-6 (Full Control)	70,1%	28,68%	0,54%	0,67%	0%	3,4234	15-38%

Figure 6.4. BBN Tunnel "Decision Support" Agent

One of the aims of this research has been identified as providing a decision support mechanism for tunnel practitioners, while carrying out a strategic risk assessment. In order to provide the decision making objective, during research development it was seen that the results of risk assessment alone is not sufficient enough and a comparative risk mitigation system has to be developed. Therefore, the strategies developed in Session 9 and summarized in Section 6.3.1 are included in the BBN Tunnel tool.

To accomplish this, after obtaining the project delay results, the tool runs the model simultaneously for the six strategies as depicted in Figure 6.2. Here, the nodes identified in these six strategies are assigned with their best states. For each of these strategies, the result of "TBM tunnel delay" is retrieved and loaded in the "decision support" window (Figure 6.4). Similar to the original project output data, probability values of each state and expected delay durations are provided for each strategy. In addition to this, in terms of strategic risk assessment perspective, the cost of adopting each of these strategies are also given. These data is given in light of Session 9. The cost data obtained in this session is gathered and proportioned with the total project budget of a current tunnel project. These percentages are calculated for each strategy and included in the decision support tool. However, it should be noted that this value consists of company specific data and would provide relative guidance for decision making rather than providing exact cost impacts on projects.

As a result, the "decision support" agent provides the expected delay for the modeled tunnel project and comparative data for different risk mitigation strategies to reduce and minimize the time overrun. These comparison data consist of both expected delay durations and the cost of implementing identified strategies. The final results table created in the right side of the window can be copied to a spreadsheet document so that the decision maker could carry out further data analysis. In the next chapter, validation of the risk assessment model and decision support tool is explained.

CHAPTER 7

VALIDATION OF BBN TUNNEL

This chapter describes the methodology and findings of validation and verification steps for the BBN risk assessment model and the developed BBN Tunnel tool. The chapter starts with a brief background on validation methods suitable for expert elicited BBNs. Then the methodology adopted to conduct the validation and verification stages are explained. Finally, the findings of each stage in the described methodology is provided to ensure the validity of the model and tool that is developed.

7.1. THEORETICAL BACKGROUND ON VALIDATION OF BAYESIAN BELIEF NETWORKS

The computerized models that are developed to aid decision making evidently aim to provide adequate system performances and correct behavior. Therefore, the model developers perform series of procedures in verification and validation tests to ensure their model is able to represent the real cases with sufficient accuracy. In order to start these procedures in this thesis, the identification of these concepts are provided below.

Model verification is the process of ensuring that the developed model works correctly and satisfies the assumptions and rules on the subject (Carson, 2002). Whereas, model validation is defined as "*substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model*" (Schlesinger, 1979). It consists of evaluating a model's level of accuracy in representation the real system behavior until a sufficient confidence is reached. In this study, a broader definition suggested by Pitchforth and Mengersen (2013) is followed. According to Pitchforth and Mengersen (2013) model validation is "*the ability of a model to describe the system that it is intended to describe both in the output and in the mechanism by which that output is generated*".

The studies on model validation agree that absolute validation of a system cannot be achieved as behavior of any model is basically constructed on approximation of a system. In addition, although level of confidence increases with the number tests, cost and amount of time increases as well (Carson, 2002; Sargent, 2009). Therefore, a certain level of accuracy is aimed to be reached during these procedures in order to consider a model is valid.

Another concern is the context and sources of validation tests conducted for BBNs. BBNs are most commonly created by eliciting expert knowledge especially in determining the CPTs of complex networks. These models are usually validated by either consulting on experts that contributed in model creation or by comparison of model outputs with empirical or literature data. Previous research on validation of BBNs use certain amount of data to test the level of accuracy in the model (Silander et al., 2009). However, when data is limited, and expert knowledge elicitation are preferred for creating these models, validation methods tend to focus on expert validation tests (Korb and Nicholson, 2010). Pitchforth and Mengersen (2013), argue that a comprehensive methodology is required for BBNs. According to Pitchforth and Mengersen (2013), the following four elements constituting a BBN which also are noted as sources of uncertainties (i.e. sources of confidences), should be addressed when conducting any validation process, namely; structure, discretization, parametrization and model behavior.

In light of these researches as it will be introduced in the forthcoming sections, the model verification and validation process adopted in this research consists of two main perspectives; 1) verification for ensuring the model and tool correctly align with the assumptions and research purpose, 2) validation for ensuring the model and tool satisfies a certain level of accuracy to be implemented as intended.

7.2. VALIDATION METHODOLOGY FOR BBN TUNNEL

This dissertation aims to develop a decision support mechanism that can be implemented in real case problems; therefore, a systematic validation is required to verify and validate both the developed BBN model and the decision support tool for its intended purpose. After examining the theoretical background on validation methods, research by Sargent (2009) and Pitchforth and Mengersen (2013) were taken as basis for developing the validation methodology. Accordingly, a Model Validation Methodology is developed in order to meet the specific needs and objectives of the research. This methodology, as given in Figure 7.1 has been created so that it aligns with the Research Design provided in Chapter 3.

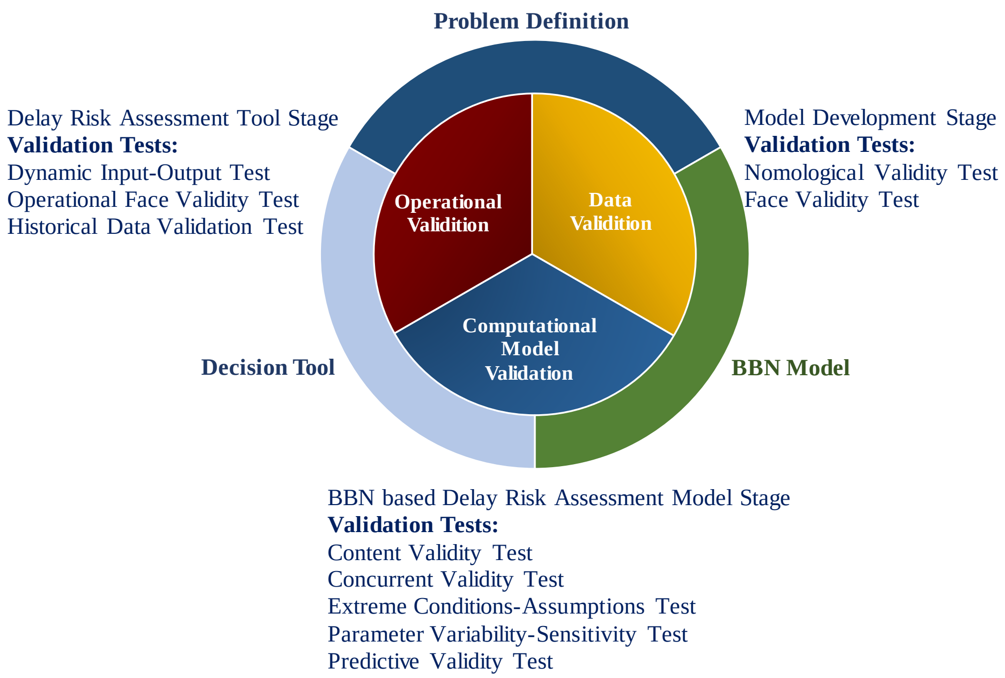


Figure 7.1. Validation Methodology

As it is defined above, the validation methodology developed in this research is based on the combination of methodologies presented by Barlas (1996), Sargent (2009) and Pitchforth and Mengersen (2013). These tests are conducted to assess the data validation, computational model and operational validation to ensure the model and tool are constructed so that they consist of adequate information and mimic the real system behavior with sufficient accuracy. The description of the tests that are performed as given in Figure 7.1and Table 7.1 are as follows;

1. Data Validation: Data Validation is carried out in development stage of the BBN based risk assessment model to ensure that data obtained to develop the model is enough and correct for using, to reach the intended purpose. In the validation methodology created for the thesis, this stage consists of examining if the data that is acquired and the risk taxonomy that is created adequately represents the TBM tunnel construction project parameters and if sub-clusters of data are created adequately.
2. Computational Model Validation: In Computational Model Validation, the BBN model is validated through set of tests. These tests consist of assessing whether the developed BBN model contains number of relations that resemble the real system sufficiently and tunnel construction projects, ensuring whether the model accurately portrays the underlying assumptions, theories and behaves according to the intended purpose.
3. Operational Validation: The Operational Validation stage consists of investigating the BBN Model output and Decision Support Tool operation. This involves testing if the model provides reasonable results, model’s logic for input-output relations are correct, tool accurately provides outputs from the model, the model and tool adequately represents the real system behavior.

As a result of this validation methodology, the developed research is aimed to be validated as a whole. In the next section of this chapter, the tests determined to conduct the above described methodology will be explained.

7.3. VALIDATION TESTS

In this research, a decision support tool together with a risk assessment model has been developed to accomplish a systematic methodology for supporting the risk management process of TBM type tunnel projects. Therefore, the validation process carried out consists of both evaluating the BBN model and risk assessment tool in order to assess if the final research output provides reasonable answers and solutions to real system problems.

Table 7.1. *The Validation Tests for BBN TUNNEL*

Validation Test	Purpose	Procedure
Nomological Validity Test	If model data domain forms part of a wider domain	Establishing group of data in the model that fits in an appropriate context in the literature, further data verification is carried out in Session 1
Face Validity Test	If model structure and relations are represented adequately	Conducted in Computational Model Chapter, an agreement on the model structure is reached by experts in Session 3
Content Validity Test	If BBN model contains all risk factors, relations and discover relations novel in the BBN model. Conduct dimensional consistency for ensuring all possible states	Content Validity questions are asked in Computational Model development stages in Session 6 and 7 to determine the novel relations, states of the nodes and their interrelations
Concurrent Validity Test	If model consists of sections/sub-networks that can be similar to networks of related theoretical subjects	Concurrent Validity questions are asked in Computational Model development stages in Session 6 and 7 to determine if the model has sub-networks related to similar construction projects
Extreme Conditions-Assumptions Test	If the evidences assigned to specified nodes provide accurate results according to assumption formulations	As described in Chapter 5, a model assumption testing procedure is conducted together with EKE in Session 8

Parameter Variability-Sensitivity Test	If the developed BBN Model displays adequate results when parameters are changed between states, key parameters correspond to real system behavior	As described in Chapter 5, a sensitivity analysis testing procedure is conducted together with EKE in Session 9
Predictive Validity Test	If the model behavior and outputs comply with real system observations	As described in Chapter 7, case project data was entered by the experts in Session 10
Dynamic Input-Output Test	If the BBN model and tool are correctly affiliated and data is correctly received from the tool that is developed	As described in Chapter 7, dynamic representation tests are conducted by researcher to test the tool and model behavior
Operational Face Validity Test	If the BBN Tunnel structure and outputs satisfy the intended purpose	As described in Chapter 7, operational face validity questions are asked in Session 11
Historical Data Validation Test	When historical data is entered, the tool should provide adequate results and decision support capabilities	As described in Chapter 7, case project data was entered by the experts in Session 12

As given in Table 7.1, ten tests are conducted throughout the dissertation, in which some tests needed modifications for satisfying certain requirements.

7.3.1. Data Validation

In data validation stage, two different tests are conducted for assessment of; having sufficient information to create the model, having appropriate causal relations and adequate representation of the problem. As many TBM construction experts are involved in model development stages of the research, it was anticipated that the model's credibility is adequate.

7.3.1.1. Nomological Validity Test

The main objective of Nomological Validity Test on the BBN model that is created through expert elicitation sessions, is to examine if the BBN structure would belong to a wider domain. In order to carry out this test, first the empirical research data is examined by the researcher. As a result, risk clusters and a risk categorization questionnaire are created by the researcher. During the first expert knowledge elicitation session (Section 4.2), these are shared with the experts. The risk clusters and the risk categorization were reviewed by the experts. The two specialists declared that the data in risk clusters adequately represent tunnel constructions and the TBM tunnel project risks given in the final risk taxonomy forms a suitable sub-group of risks involved in tunnel projects.

At the end of this session, the experts are asked to identify if some of these TBM tunnel project risks form a smaller section in tunnel projects. They have marked and thus identified the following nomological "adjacent risk factors" that would be shared among other tunnel projects as given is Table 7.2.

Table 7.2. *Nomological Validity Test, Adjacent Risk Factors*

Risk Factor
Explosive Gas Leakage into Tunnel
Unexpected Ground Conditions
Detail of Ground Surveys
Effectiveness of Soil Improvement before Excavation
Unexpected Alignment Revisions
Inconsistency Between Design Assumptions & Construction Method
Overconfidence in Construction methods
Health and Safety Issues
Late Site Access
Different Circumstances Compared to Data from Authorities
Employer's Additional Requirements
Delays in Site Access
Delays in Advance Payment
Delays in Material Supply
Material Loss during Transportation
Delays in Progress Payments
Delays in Customs Clearance
Tunneling below Historic Artefacts

7.3.1.2. Face Validity Test

After the nomological validity test, the BBN model is created through a mapping procedure with expert elicitation sessions as described in Chapter 5. The face validity test is carried out to determine if the created BBN model structure satisfactorily reflects the real system. This is established from the viewpoint of the experts through asking questions about the model. After the finalized BBN model structure is constructed in scope of Sessions 2 and 3, based on the work by Pitchforth and Mengersen (2013), the following questions have been addressed to the experts at the end of Session 3;

1. Is the model network structure adequately represent TBM Tunnel Projects?
2. Are the parent-child relationships, risk events and consequences adequately constructed for the intended research purpose?
3. Is the detail level of the network sufficient to include all necessary relationships for delay risk factors for TBM Tunnel projects?
4. Are the sub-networks in the structure provide a detailed assessment base for accomplishing delay prediction?

At this stage, the experts reviewed the network structure as noted in Section 5.3. and as a result of a brief brainstorming session, it was concluded by the experts that the hierarchical structure of the network resembles the real system behavior for the intended research purpose. The sub-networks of the model are found adequate and the levels of parent-child trees are constructed in sufficient detail.

7.3.2. Computational Model Validation

After the model structure is verified by the experts, the BBN model is created in the software architecture by the researcher. As detailed in Chapter 5, during development of the BBN Tunnel model, the experts determined the states and CPT assignments. After that, Direct Structure Validity tests (Barlas, 1996) are conducted through

Content Validity and Concurrent Validity tests by the researcher and the experts during the sessions described in Chapter 5.

The aim of these procedures are to compare the empirical knowledge with the developed model. Then, validation of computer model is concluded by the Structure Oriented Behavior tests (Barlas, 1996) in Extreme Conditions-Assumptions test and Parameter Variability-Sensitivity test, created by the researcher and verified by the experts, to evaluate the behavior of the structure through implementations. As a result of these computerized model validation tests, the final BBN model is formed.

It should be noted that, due to the successive steps carried out to develop the BBN Tunnel tool based on the created risk assessment model, specific validation steps are incorporated in the development process of this thesis. Additionally, in certain tests that are elaborated in this section, some additional boundary conditions were added due to the suggestions of the experts and these were demonstrated to the model. Therefore, the level of confidence in the model increased throughout the validation procedures.

At the end of this stage, a further interview session is conducted with a specific expert for the Predictive Validity Test to examine if the model behavior fits with real system parameters. Here, real case projects are modeled with the developed BBN and the results are compared with actual observations on these projects.

7.3.2.1. Content Validity Test

The Content Validity Test is carried out to determine if the model consists of all required nodes and relations necessary to interpret the problem. The procedure involves an observational structure with information obtained from real system therefore, it constitutes of comparing the model structure with the empirical knowledge on the system that is intended to be represented.

In line with the methodology presented by Pitchforth and Mengersen (2013); the two experts in Session 6 and Session 7 were asked to assess the content validity of the

BBN model in terms of the number and range of states, CPT tables that consist of the probabilistic relations among the parent-child nodes and the irrelevant states that should be eliminated for model behavior. Each state of the nodes and the relations between the nodes are reviewed and modified by the experts if seen necessary. For instance, the project duration states, the final tunnel delay states are modified, irrelevant states are eliminated and duration ranges between specific nodes are agreed. As it was given in Chapter 5, final CPT tables and relations were found adequately detailed to represent the intended problem.

7.3.2.2. Concurrent Validity Test

As the final part of the direct structure validation tests, the concurrent validity is carried out to determine if the BBN model contains sub-networks that can be shared with sections of other networks of similar theoretical subject. In order to assess this, similar to the Content Validity Test, the experts in Sessions 6 and 7 are requested to evaluate the model structure. The experts are asked to determine if there are certain network groups which can be valuable for other problems for example such as NATM type tunnel projects.

According to the evaluations of the experts in Session 6 and 7, the sub-networks that can be used in other type of construction projects are determined based on the risk events given in the BBN model. More specifically, the sub-groups given in Table 7.3. were found valuable for using in other problems to determine the delay risk probabilities.

Table 7.3. *Concurrent Validity Test, Sub-Networks*

Risk Event	Risk Factor
Detail of Geotechnical Design	Explosive Gas Leakage into Tunnel
	Unexpected Ground Conditions
	Detail of Ground Surveys
	Effectiveness of Soil Improvement before Excavation
Contractor's Experience	Overconfidence in Construction methods
	Health and Safety Issues
Experience of Workers	Experience of TBM Operator
	Performance of Segment production Sub-Contractor
Country of Construction	Delays in Site Access
	Delays in Advance Payment
	Delays in Material Supply
	Material Loss during Transportation
	Delays in Progress Payments

7.3.2.3. Extreme Conditions-Assumptions Test

After the BBN based delay risk assessment model is finalized through Direct Structure Tests, the model is completely transferred to the SAMIAM software and mathematical testing formulations are produced by the researcher for the Structure Oriented Behavior Tests. These formulations are then induced to the BBN Computational Model via the SAMIAM software tool.

The extreme conditions test is aimed to determine the numerical consistency of the CPT assignments, the model's logical behavior in assignment of extreme evidences that are formulated through the assumption formulations and behavior of the model under extreme condition assignments compared to the real system behavior.

In the extreme testing the assumption tests are developed by the researcher so that the states are assigned to their extreme values. During these tests, as it is detailed in Section 5.4.3, the following assumption testing conditions are determined by the researcher;

- The sum of probabilities for each node should be equal to 100%.
- TBM machine can only be stuck if type of TBM machine is “Hard Rock Open Type”, otherwise the probability is equal to zero.
- When TBM stoppage reaches 4-6 months the tunnel delay is expected to be minimum 4 months therefore, “Delay TBM” state in this condition should not be “very low”.
- Respectively, start of project is delayed “more than 6 months” then “Delay TBM” state cannot be “very low”. If equipment/building repairs take up to 4 months, then “Delay TBM” state cannot be “very low”.
- In case where project start delays to its maximum, the operational delays, TBM stoppage and equipment/building repair durations reach to their maximum values (6 months) then “Tunnel Delay” should be more than 12 months.
- Although unlikely in most cases, if concrete segments do not meet the tunnel geometry requirements, major design revisions will certainly be required.
- Due to the cost perspective of these specialized tunnel projects, if the duration of the tunneling is relatively low (18-24 months) the number of TBM machines would not be more than six.

After these formulations are developed by the researcher, each of these conditions are shared with a TBM tunnel expert in Session 8. The outputs are discussed in terms of real system behavior and additional remarks are requested from experts as given in Session 8 of Section 5.4.3. The expert reviewed and noted that an addition to these test conditions shall be provided. According to the expert; when the TBM machine gets trapped in soil as given in ACF 2, the time required to overcome this problem would not be less than 6 months. Thus, the assumption testing is carried out and a modification in the CPTs is made to in the BBN Model via the SAMIAM Sensitivity Analysis window to satisfy this case. After this modification is done, the previously carried out tests are re-run to assess if the created formulations are still satisfied. Due to the limited space of this research a section of the CPT assignments reviewed and found appropriate by the expert is given in Figure 7.2.

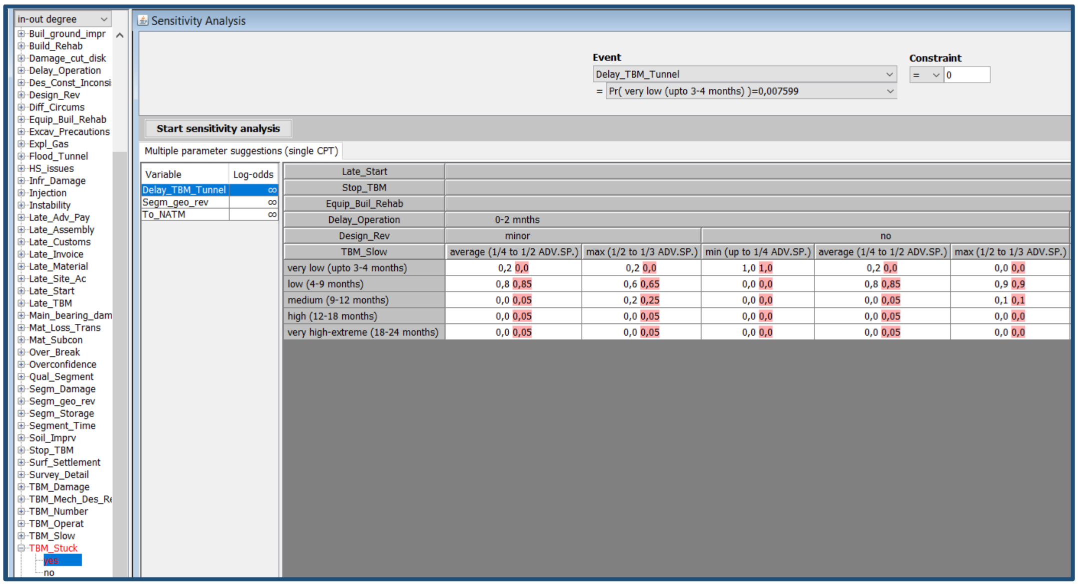


Figure 7.2. Section of CPT parameters modified in Extreme Conditions-Assumptions Test

Nine assumption testing runs were conducted together with the presence of an expert and after one modification implemented to the model, it was decided that the final BBN model gave reasonable outputs compared to the real system behavior.

7.3.2.4. Parameter Variability-Sensitivity Test

The parameter variability – sensitivity test is aimed to determine if the changes in parameters are consistent with the behavior of the real system. Based on the works of Barlas (1996) and Sargent (2009), each of the model parameters are tested to identify the ones that the model is highly sensitive. The researcher carried out a comprehensive analysis to test each node to its best-worst state. Then expected values of each output is calculated and compared as it can be seen in detail in Section 5.4.4. After these outputs are graphically visualized, the results are discussed with the experts in Session 9. At this stage of the study, the model is verified through finished tunnel constructions and also progressing recent real case projects in Turkey. As the experts reviewed the outputs of the sensitivity analysis, it was concluded that the BBN based model is valid under the parameter variability conditions. The list of sensitivity parameters are given in Section 5.4.

7.3.2.5. Predictive Validity Test

The predictive validity test constitutes the last stage of BBN Model verification process in which the model outputs are compared with real system behavior. In order to accomplish this, Session 10 is conducted for expert knowledge elicitation as details are given in Table 7.4. Based on the research of Pitchforth and Mengersen (2013), the procedure is designed so that, the developed model behavior is tested through case study projects with experts and comparing their results.

Table 7.4. *Predictive Validity Session*

Session 10: Information	
Purpose:	Evaluating the model behavior and comparing the outputs with real system
Type:	Interview
Duration:	3 hours without break
Participants:	Division Manager: 20 years tunnel construction TBM operation field experience
Procedure	
Pre-Session:	SAMIAM BBN Model (final)
Input:	Three case project data are entered as evidences to the SAMIAM BBN Model • Purpose of projects: wastewater transmission tunnels in various locations in İstanbul • TBM properties: 2.2 meters inner diameter EPB Type
Methodology:	Description of projects Assignment of evidences according to the project properties
Tools:	Interview SAMIAM
Output:	TBM Tunnel delay durations • The projects possessed similar properties with average duration of delay 6 months
Anonymity:	The company allowed to gather expert data. However, the project names of which the data is acquired is not permitted to be shared directly.

During this predictive validation session, data from three wastewater tunnel projects are entered into the BBN model. The projects are selected as the expert encountered and solved critical tunnel construction problems. The expert that is consulted in this test has 20 years of expertise in the TBM tunnel works and was able to interfere high risk situations in these projects. As the TBM expert sets evidences to each node in the model, it was ensured that the BBN model is valid under the Predictive Validity Session (Appendix-J). Therefore, the output of the model was concluded to be working correctly by the expert.

7.3.3. Operational Validation

After the data validation and computational model validation stages are completed and the BBN model is verified, the decision support tool is developed by the researcher. The processes carried out for this purpose is described in detail in Chapter 6. In the next stages of the research, the developed BBN Tunnel tool is aimed to be assessed through operational validity tests that are ran to ensure the system is observable, accurate and satisfies a certain level of accuracy. In this context, operational face validity tests, historical data validation test and a dynamic input-output test (Sargent, 2009) are carried out for assessing the behavior of the generated tool.

7.3.3.1. Dynamic Input-Output Test

After the computational tool is developed, a series of dynamic input-output tests are carried out by the researcher to ensure the tool and model are integrated and the tool retrieves data from the model correctly. In order to observe the output behavior of the tool, each problem parameter is assigned with its every possible state through the BBN risk assessment model as well as the risk assessment tool. Total of 45 evidence assignments for the twenty nodes are entered in the BBN model. The results are compared with the output given in BBN Tunnel. Similarly, to examine the results of strategic risk assessment, totally 76 x 20 = 1520 strategy assignments are induced in the BBN model. Each of these outputs are compared with the BBN Tunnel output results. As a result of these series of assignments, it is seen that the tool is able to correctly assign the relevant nodes to the BBN model and correctly read the probability distributions that are calculated through the inference engine of the MSBNx model.

7.3.3.2. Operational Face Validity Test

The face validity test for operational validation is carried out to understand, if the model's behavior accurately provides decision support properties for real systems from the expert's point of view. It is partly similar to the face validity test conducted in data validation however, the test in this stage is more directed towards assessing the behavior of computational tool rather than the BBN model. The test is conducted by sharing it with the expert that participates in session 12 beforehand, for asking the following set of questions;

1. Does the decision support tool provide valuable information for assessment of delay risk in TBM tunnel projects?
2. Are the root nodes and sensitivity parameters adequate for data collection stages in the assessment process?
3. Is the user interface understandable for the decision makers in the industry?

At this stage, the expert reviewed the structure of the tool and recommended some modifications in the user interface in scope of question three. Previously only delay probabilities were provided in the "decision support" Window. When recommendations of the expert is performed the final structure as seen in Figure 6.4, BBN Tunnel is shared again with the same expert and then the final tool is concluded to be adequate and practicable in real systems for decision support purposes.

7.3.3.3. Historical Data Validation Test

After the tool is validated through the operational face validity test, a separate session is conducted with the expert to determine if the tool provides valuable information for a concluded tunnel project. The details of the session are provided in Table 7.5.

The aim of this test is to assess whether the tool behaves as the model does and if the output data is relevant for the real case system when a part of data required by the tool is entered (Sargent, 2009). The historical data validation test is conducted with a project manager with experience in tunnel construction consultancy projects both in the design and construction stages.

Table 7.5. *Historical Data Validation Test Session*

Session 12: Information	
Purpose:	Historical Data Validation Test
Type:	Interview
Duration:	3 hours without break
Participants:	Project Manager: 15 years TBM tunnel consultancy experience
Procedure	
Pre-Session:	Evaluating the outputs of the tool and the impacts of strategies
Input:	Real case project data as tool's input parameters
Methodology:	Description of input parameters, Implementing a real case project via the BBN Tunnel Tool, Discussion of results
Tools:	Interview, BBN TUNNEL Tool
Output:	Delay durations, strategy delay and cost impacts
Limitations:	Reliance on expert judgements, Excessive time to get the experts familiarize with the details of parameters and strategy formulations, Excessive time for experts to review and assess the outputs especially in terms of cost impacts
Anonymity:	The company allowed to gather expert data. However, the name of project of which the data is acquired is not permitted to be shared directly as they reflect actual financial and workforce data of a government funded project.

Table 7.6. *Input Data for Data Validation Session*

Input Data	
TBM Procurement Method	Purchase
Country of Construction	National
Experience of Workers	Experienced
Construction Place	Urban
Duration of Project	More than 36 months
Detail Level of Tunnel Design	Detailed
Detail Level of Geotechnical Design	Adequate
Experience of Main Contractor	Adequate
Detail Level of Cutterhead Design	Adequate
Damage to Infrastructures	No
Flooding Tunnel	Yes
TBM Mechanical Design Review	No
Explosive Gas	No
TBM Damage	No
Survey Detail	Roughly Prepared
Segment Production Area	Enough
Segment Geometry Revision, Additional Employer Requirements, Health and Safety Issues, Tunnel Historic	No

The input values of finished TBM tunnel projects is entered in BBN Tunnel with the expert. The outputs generated from the tool are reviewed and discussed with the expert following the analysis to understand the behavioral and operational validity of the tool.

When historical data is entered to BBN Tunnel by the expert as seen in Table 7.7, the tool is concluded to give adequate results and decision support capabilities.

Table 7.7. *Results of Historical Data Validation Session*

Output Data	
Current Project Delay (Exp. Value)	7.2 months
Strategy-1 (Geotechnical Design) Delay	4.5 months
Strategy-2 (H&S Precautions) Delay	4.8 months
Strategy-3 (Design Revision) Delay	6.4 months
Strategy-4 (TBM Advancement) Delay	4.9 months
Strategy-5 (Partial Control) Delay	4.0 months
Strategy-6 (Full Control) Delay	3.4 months

According to the strategic risk assessment procedure, the project delay was able to be decreased to 4 months, which was achieved after taking precautions for TBM Advancement as detailed in Strategy 4. However, it was emphasized by the expert that the cost impacts of the results provide rather forecasted ranges and the decision makers shall be aware of this and carry out their cost estimations specific to the projects rather than assuming these as exact amounts.

CHAPTER 8

IMPLEMENTATION ON A CASE STUDY PROJECT

This chapter describes implementation of the BBN Tunnel on a real case study metro tunnel project. In order to do that, first information on the selected project is summarized and then it is utilized in BBN Tunnel. In the last section, the results of the implementation are discussed, expert's opinions on the results and their evaluations on BBN Tunnel are provided.

8.1. REAL CASE TESTING

After the computational risk assessment model and BBN based risk assessment tool are built and verified, the implementation stage is planned in this section in order to show how the developed tool is utilized to carry out the delay risk assessment methodology developed in this thesis. The process is aimed to describe how data are entered into BBN Tunnel and how accurate its results are compared to BBN model and real case implemented projects. Here, after the real tunnel project is identified and defined by the experts, it is utilized in BBN Tunnel and its results are compared with actual project outcomes. Thus, implementation consists of three steps; 1) identification of real case project information, 2) implementation through the BBN based delay risk assessment model and BBN Tunnel, 3) analysis of the project outputs through real case testing. The project outputs are examined in terms of; the project delay durations, and potential results of strategy implementations. These two examinations constitute the real case testing process.

Since the BBN model or the decision support tool do not aim to make a precise estimation, the aim in this real case testing procedure also is not to show the precision of the calculations. Rather than this, the testing is conducted to assess the usability of the tool in real case projects. Therefore, the implementation and testing procedure consists of three main steps; entering data to BBN Tunnel, analysis of outputs obtained (i.e. probability of delays), analysis of the strategies calculated.

The main indicator was selected as the variance of probability values for time overrun that are calculated by the model and the tool. Based on this main indicator, the real case delay durations are compared with, the implementation results for delay durations and strategy outcomes. Thus, implementation is carried out in two stages. In the first stage, the results of the BBN model and BBN Tunnel are compared. In the second stage, the strategies are evaluated through an expert knowledge elicitation session. Both of these stages are conducted in the presence of experts that have already taken part in the implementation of the case project.

8.1.1. Identification of Project Information

As mentioned before, the case study implementation project is a metro tunnel project. It is an 18 km long TBM tunnel which is connecting İstanbul's populated subway lines with 15 stations. The project has been recently completed and its data has been gathered from experts in a spreadsheet form prepared by the researcher prior to the session 13. The summary of information that has been obtained for implementation is given in Table 8.1.

Table 8.1. *Summary of the Case Study Project*

Name	Property	Name	Property
CONSTRUCTION PLACE	Urban with no surface access	**DETAIL OF GEOTECHNICAL DESIGN**	Detailed
COUNTRY OF CONSTRUCTION	National	**ADDITIONAL EMPLOYER REQUESTS**	No
LENGTH OF TBM TUNNEL	18 km	**BUILDING REHABILITATIONS**	Yes
NUMBER OF TBM MACHINES	Three	**TUNNEL INSTABILITY**	Yes
TUNNEL CONSTRUCTION DURATION	Approximately 42 months	**INFRASTRUCTURE DAMAGE**	No
CUTTERHEAD DAMAGE	Yes	**TYPE OF TBM**	EPB TBM
WELLS	Yes	**EXPLOSIVE GAS**	No
INJECTING THE WELLS	Yes	**FLOODING TUNNEL**	No
MAIN BEARING DAMAGE	No	**SEGMENT GEOMETRY REV.**	No
TBM DAMAGE	No	**DELAYS IN TBM SUPPLY**	No

8.1.2. Implementation on the Case Study

Implementation of the real case project is conducted in a focus group discussion session with two experts. As given in Table 8.2, the experts in the implementation session are two specialists involved in the case study project until its start and are from two different positions (i.e. one from the consultancy position and the other from the TBM field operations position). Therefore, it was accepted that the two experts can adequately analyze the findings of the test from different points of views and evaluate the impacts of mitigation strategy formulations. To start the implementation, data summarized in Table 8.1 are entered to BBN based risk assessment model as described in Chapter 5. Evidences of each node are assigned in the model. Then the same data are entered to BBN Tunnel as described in Chapter 6. This involved selection of project properties from the dropdown-box from the problem definition agent. These two data entry steps are implemented by the experts as given in Table 8.2. The comparison of results calculated by the BBN Model and the Decision Support Tool are given in Table 8.4.

Table 8.2. *Case Study Modeling and Real Case Testing Session*

Session 13: Information	
Purpose:	Implementation of the Case Project and Strategy Testing
Type:	Focus Group Testing and Discussion
Duration:	5 hours with one break
Participants:	Project Manager: 15 years TBM tunnel construction consultancy experience Division Manager: 20 years tunnel construction TBM operation field experience
Procedure	
Pre-Session Study:	Real case project data gathering spreadsheet table developed by the researcher and entered by the experts

Input:	Real case project data as input parameters BBN Tunnel Model and Tool
Methodology:	Description of model input parameters Entering data as evidences via the BBN Model and BBN Tunnel Tool Discussion of results with experts on actual project outcomes Obtaining feedbacks on the outputs of the tool and its decision support capabilities from the experts
Tools:	Focus Group Interview BBN Model and Tool
Output:	Delay probabilities, their corresponding expected values Strategies, their delays and their cost impacts
Limitations:	Excessive time to get the experts familiarize with the details of parameters and strategy formulations Excessive time for experts to review and assess the outputs especially in terms of cost impacts
Anonymity:	The company allowed to gather expert data. However, the name of project of which the data is acquired is not permitted to be shared directly as they reflect actual financial and workforce data of a government funded project.

8.1.3. Findings of Real Case Testing

In this step, the experts compared the results of the model, the tool and the actual project outputs, discussed the strategies and their impacts on the project. This process is carried out in two stages. In the first stage, the real case project summarized in Table 8.1 is entered into BBN Tunnel. Then the results of the project are compared with the actual delay conditions occurred. The results of the first stage that involves comparing the model and tool outputs are given in Table 8.3.

Table 8.3. *Comparison of Results Generated by BBN Tunnel*

Output Data	BBN Model	BBN Tunnel
Probability of very low delay (upto 4 months)	-	3,25%
Probability of low delay (4-9 months)	57,27%	40,7%
Probability of medium delay (9-12 months)	39,44%	51,68%
Probability of high delay (12-18 months)	3,29%	4,36%
Probability of very high delay (18-24 months)	-	-
Expected delay (months)	8,4 months	8,8 months

As it can be seen from Table 8.3, results of the model and the tool are different from each other. As it is described in Chapter 6, the risk assessment tool is created in light of the sensitivity analysis results. In order to automate the risk assessment method, the tool consists of the sensitivity risk factors only and the tool input data assigns only these parameters to the BBN Model. Therefore, as not all project data is entered into the BBN Model, a certain level of variance is expected to be obtained. However, as mentioned in Chapter 7, the tool aims to provide a more practical solution that approximates the actual result and as the difference is negligible, the results are evaluated to be valid in terms of resembling the real system behavior.

Probability of Delays: The delay probability values calculated in the BBN model was different from the results obtained from BBN Tunnel. It was seen that the skewness of the data is shifted towards the higher delay probability in the tool. The probability of low project delay is calculated as 57,27% in the BBN model whereas it was calculated as 40,7% in the tool. On the other hand, probability of medium delay in the BBN model is calculated as 39,44% and it is calculated as 51,68% by the decision support tool. Tunnel experts argued that, these results could be influenced by many uncertainties that could be observed in tunnel projects. Thus, such a shift in skewness is concluded to be acceptable. As the tool rather aims to provide an insight to the decision makers, it was concluded that these probability distributions provide valuable information and the tool can be used for evaluating impacts of different risks involved in these projects.

Expected Delay: The expected delay is calculated by multiplying the average duration of delays and their corresponding probability of occurrences. This formula is given in Section 5.4.4. When the results of model and tool are compared, 5% variance between the expected delays are seen which corresponds to a 95% adequacy ratio. Tunnel experts discussed that this difference is rather acceptable, and the results are successful in representing the real project behavior. The real case project concluded with 8-9 months delay, thus the experts concluded that both the tool and the model provide accurate results. The experts also concluded that this expected delay value provide more valuable information in terms of decision support, compared to probability distributions of each state.

Table 8.4. *Evaluation of Results Generated by BBN TUNNEL Tool*

Project Strategy	Probability of very low delay (upto 4 months)	Probability of low delay (4-9 months)	Probability of medium delay (9-12 months)	Probability of high delay (12-18 months)	Probability of very high delay (18-24 months)	Expected delay (months)	Cost (% of Total Cost)
Current Project (No Strategy)	3,25%	40,70%	51,68%	4,36%	0%	8,8	-
Strategy-1 (Geotechnical Design)	11,13%	46,02%	39,93%	2,91%	0%	7,8	3-7%
Strategy-2 (H&S Precautions)	6,03%	42,54%	47,57%	3,86%	0%	8,5	5-8%
Strategy-3 (Design Revisions)	53,08%	43,24%	2,42%	1,27%	0%	4,3	5-10%
Strategy-4 (TBM Advancement)	7%	77%	16%	0%	0%	6,8	8-12%
Strategy-5 (Partial Control)	57,50%	39,86%	1,76%	0,88%	0%	4,1	12-18%
Strategy-6 (Full Control)	70,03%	28,75%	0,55%	0,68%	0%	3,4	15-38%

In the second stage, the strategic risk assessment results are discussed with the experts. In order to accomplish this, the results of BBN Tunnel as given in Table 9.5 are examined by the experts.

Strategy-1 (Geotechnical Design) Delay: As described in Chapter 6, this strategy aims to minimize the delays caused by uncertainties involved with vagueness in geotechnical design. From the analysis results calculated by the tool, the expected duration of delay is decreased from 8,8 months to 7,8 months. After detailed information about the nodes that this strategy affects is provided, the experts in session 13 found it adequate that the consequence of the precautions taken would provide saving time for approximately one month. They have also checked the corresponding cost percentages for the case project and confirmed the percentage intervals.

Strategy-2 (H&S Precautions) Delay: In the second strategy, health and safety conditions are improved through either insurance or safety preventive measures. It was calculated that the result of these measures provides only a slight change in the time overrun risk. This was also found adequate by the experts due to relatively shorter durations to overcome the risks involved in this strategy. However, due to high insurance costs the cost percentage of this strategy increases comparatively.

Strategy-3 (Design Revision) Delay: The scenario for minimizing design revisions is calculated to be one of the most influential strategies for the case project, corresponding to a decrease to 4,3 months delay almost reducing the original project delay to half. In order to give insight to this strategy, the details of the nodes and the explanation of the countermeasures are summarized to the experts.

In light of these; it was concluded by the experts that the design revisions necessitated during the project in hand; primarily due to unexpected ground conditions, excavation-support measures, building improvements and tunnel instability, resulted with high delays on project durations. Therefore, the experts found it adequate that this strategy would decrease the project delay durations significantly. Subsequently, the costs involved to decrease these risk factors which also involve the precautions in strategy one, would become comparatively higher than the previous strategies.

Strategy-4 (TBM Advancement) Delay: The TBM advancement strategy as described in Chapter 6, involves eliminating operational delays and causes, that slows down the boring process. These include TBM supply and design delays, segment construction delays and obstructions met during tunnel boring. When these risk factors and the measures to overcome these risks are explained to the experts, they have discussed the results and the decrease in expected delay from 8,8 to 6,8 months. As a result, it was evaluated that the actual slowdown in the project was minor. The obstacles occurred in terms of slowing down the TBM boring speed did not reach critical levels thus, the two months delay output was found adequate for the project. Likewise, the corresponding costs of the listed measures was found approximately accurate.

Strategy-5 (Partial Control) Delay: In the partial control strategy, there are many risk factors involved to decrease the strategy but without taking costly measures such as additional TBM machines or other operational changes. This aimed to provide an alternative to the last strategy but with a less cost to reach an agreeable amount of delay. This perspective has been explained to the experts with the risk factors that are aimed to be addressed, precautions and their objected impacts. The resultant delay duration in this case decreased to 4,1 months, more than half of the original project delay. They have finally agreed that this comprehensive strategy would provide the calculated results both in terms of durations and costs.

Strategy-6 (Full Control) Delay: The last strategy has been created to observe the best-case scenario for the tunnel project that will result with the minimum delay possible. Therefore, all of the risk factors are assigned with their best-case states through the developed BBN Tunnel tool and the costs for accomplishing these are added. The resultant delay duration has been able to be decreased to 3,4 months with a relatively high cost. The experts evaluated the results and noted the delay duration to be sufficiently accurate. However, when they have examined the cost they have questioned the wide percentage interval. They were finally satisfied to find out that this range has been calculated for different tunnel lengths and construction durations that contribute to the operational and tunnel boring delay factors specifically involved in this strategy.

8.2. DISCUSSIONS ON IMPLEMENTATION RESULTS

According to the outputs of the BBN Tunnel tool, the original tunnel project is expected to be completed with an 8,8 month delay. Activities in the schedule with the greatest sensitivity to achieving the target completion date are; the mechanical design revisions, tunnel safety, geotechnical survey details followed by TBM advancement speed and TBM tunnel operational activities. Additionally, the most important risk consequences (i.e. leaf nodes in the BBN model) were found to be TBM stoppage and equipment and building rehabilitations.

The implementation of the BBN based risk assessment model and developed decision support tool on a real case was found to be satisfactory by the experts. It was stated that the implementation of the tool in the project initiation stage as well as in the course of the project, examining the anticipated delays and the mitigating measures can support the decision-making procedures during risk assessment practices. The results of the real case project have also been compared with the actual case project results. Accordingly, the experts emphasized that the actual tunnel delay fits successfully with the 8-9 months calculated by the tool. The strategies were also evaluated, and it was said that the clustering of each mitigation scenario and the calculation of their effects provide a significant contribution to the tunnel construction sector.

Among the six risk mitigation scenarios, strategy three was found to be the most preferable choice. Due to the risk factors dominating the case project, minimizing design revisions was found to provide a satisfying decrease in the project delay. Apart from this, the costlier options are considered as strategy five and six. The experts noted that these options could also be chosen by decision makers, in cases where there is a high public/employer pressure to finish the tunnel construction earlier than it is planned. The cost impacts of the mitigation strategies are also discussed with the experts. They have pointed out that it was highly valuable that the tool addressed the time and cost perspectives together. In addition, they specified that these percentages calculated by previous data that are obtained by the researcher provide adequate intervals.

However, they have noted that these values correspond to the metro tunnel projects consulted by the same company that were used to develop the tool and although the comparative cost percentages between the six strategies adequately portray the relative impacts on projects, other types of tunnel constructions would require adjustments in the actual cost percentages.

In summary, the BBN based delay risk assessment model and decision support tool was found satisfactory and useful for risk assessment in TBM tunnel projects. It was emphasized that the tool makes it possible to implement the mathematical model, provides a practical way to use the BBN computational model and aid potential users in formulating strategies to mitigate risk of delay.

It should be emphasized again that; the tool and embedded strategies are company-specific and cannot be generalized. Similar tools can further be developed considering different objectives, preferences and strategies of companies by following the process proposed in this thesis.

CHAPTER 9

RESULTS AND CONCLUSIONS

In the last chapter of this research, the summary of the thesis and the main contributions of the developed decision support tool are presented. Therefore, the chapter starts with a summary of the stages implemented in this research. In the second part, the results of the methodology is given, model features and capabilities are outlined, and main expected benefits of the developed method and the decision support tool are identified in terms of project risk assessment literature and the tunnel construction industry practice. In the final part, the chapter concludes with recommendations for further improvements and future works.

9.1. SUMMARY OF THE RESEARCH

When the literature and practice is examined on risk assessment methods for tunnel projects, it is seen that these studies tend to either focus on part of the problem domain, underestimate the time impacts of project risks or administer intuitive based methods. In practice, generally qualitative risk analysis methods have been implemented to assess project risks. However, these methods did not take into account the interdependencies among different risk sources and thus could not provide numerically correct estimates of the overall project risk. The literature researches on the subject has been focused on a specific problem and could not provide a comprehensive risk assessment method.

Thus, the main aim of this thesis is identified as, to develop a novel risk assessment method and a decision support tool for delay prediction in tunnel projects, that incorporates the Bayesian Belief Networks' dependency analysis, expert elicitation procedures and strategic risk assessment. In order to accomplish this, a six phase research methodology is developed to carry out the research (Section 3.5); 1. Research design, 2. Risk taxonomy, 3. Computational model, 4. Decision support tool-BBN Tunnel, 5. Validation of the model and the BBN Tunnel tool, 6. Implementation of real case tunnel projects.

In the first phase, literature studies are reviewed. Then, a case study research is conducted with collaboration of a real construction company. The actual risk assessment reports are examined. In light of these examinations and literature studies, seven major knowledge gaps are identified. It was seen that the methods were focused on a single risk source and most of the studies and implications focused on geological factors or safety risks. However, effects of different project participants, design processes, mechanical aspect of tunnels have not been united in one single risk assessment work. This has limited diagnosing the problems in tunnel constructions in terms of delay risks. Therefore, a comprehensive risk taxonomy was required. Additionally, the methods in practice mostly involve qualitative techniques and ignores calculation of the interrelations between risk factors. This has been attributed due to the complex relations, time and costs involved during these procedures prevented developing a quantitative risk assessment method in tunnel projects. The risk mitigation strategies have also been identified in some of these works however, their impacts on project outcomes have been usually neglected. Thus, the developed method is required to include a comprehensive risk assessment method and a risk handling perspective. As a result of these limitations and objectives, a sequential research design is created that has three phases namely; developing delay risk taxonomy, developing the computational risk assessment model and creation of the decision support tool. In light of these, the chapter concludes by creating the research methodology, which describes the stages that are carried out in the thesis.

In the second phase, as identified in the research design, a comprehensive risk taxonomy is developed as described in Chapter 4. This process involved examining the risk assessment literature, real case tunnel projects and carrying out expert knowledge elicitation sessions with tunnel practitioners. In light with these, risk clusters are formed, delay risks are identified and verified by the experts and as a result a comprehensive risk taxonomy is created. This risk taxonomy constituted the main input data to portray the system in the BBN model.

The third phase involves development of the BBN based risk assessment model, as described in Chapter 5. It involves creation of the qualitative and quantitative aspects of the BBN model. The model provides a graphical representation of the risks involved in TBM tunnel projects in a Bayesian network structure and a quantitative risk assessment model to predict delay. To create this computational model, series of expert elicitation sessions are conducted. As a result of these sessions, the BBN structure, dependencies between risk factors and CPT tables are determined. In the concluding part, sensitivity analysis is carried out to identify critical risk factors for project time overruns.

In phase four, a decision support tools is developed based on the BBN model which is basically a strategic risk assessment tool entitled as BBN Tunnel. Initially a strategic risk assessment procedure is defined in which, risk mitigation strategies and the cost of adopting these are determined with the experts. Then, the tool is created by the researcher, that communicates data between users and the BBN based model. The tool contains two parts namely; problem definition and decision support agents. Problem definition section enables the user/decision maker to enter data to the developed BBN model whereas in the decision support section, outputs can be retrieved in terms of project risk assessment and strategic risk assessment perspectives as identified in Chapter 6.

The fifth phase is carried out to verify and validate the model and the risk assessment tool created. In order to do this, a model validation methodology, based on the works of Barlas (1996), Sargent (2009) and Pitchforth and Mengersen (2013) is developed specific for the research. This methodology consists of three main steps; data validation, computational model validation and operational validation (Chapter 7). Similar to the other phases in the research, the validation section involved participation of experts. During this phase a total of ten tests have been carried out namely; Nomological Validity Test, Face Validity Test, Content Validity Test, Concurrent Validity Test, Extreme Conditions-Assumptions Test, Parameter Variability-Sensitivity Test, Predictive Validity Test, Dynamic Input-Output Test, Operational Face Validity Test, Historical Data Validation Test.

In the sixth and final phase of the research, BBN Tunnel is utilized to implement a real case TBM tunnel project. Together with the involvement of two experts, the project properties are identified and entered in the model and tool. Secondly, BBN Tunnel is used to test if it reflects the real system behavior, to identify advantages/disadvantages in utilizing the tool for evaluation of different risk mitigation strategies.

9.2. DISCUSSION OF FINDINGS

Time overrun is one of the main concerns in any tunnel construction project due to political and society pressures, the linear operational procedures that are involved and its contribution to cost overruns. Thus, time perspective becomes the critical aspect in these projects as it also impacts the budget in terms of expenses to overcome interruptions and damages in the tunneling advancement.

As mentioned before, this thesis has two main objectives: to develop a comprehensive probabilistic delay risk assessment model and develop a decision support tool for determining the most feasible strategies for handling delay risks in TBM tunnel projects. The system is based on the Bayesian Network technique and quantitative analysis of project uncertainties. The final BBN Tunnel tool provides a novel delay risk assessment method, with probabilistic delay risk analysis for examining how probable it is to complete TBM tunnel projects within a specified time and a decision support mechanism for evaluating between different risk mitigating strategies. In line with these, findings of the developed method have been observed in two perspectives; in terms of the most important risk factors involved in TBM tunnel projects, in terms of the most effective risk mitigating strategies that can be implemented to provide risk reduction.

In order to accomplish the first perspective, the results of the sensitivity analysis are examined. As given in Chapter 6, the sensitivity analysis is performed based on the research by Sargent (1983) and Laskey (1995). From the extreme states analysis, it was seen that mechanical failures and tunnel flooding are the most important events in TBM tunnel projects. Due to durations it takes to overcome the impact of these risk, the project durations increase more critically when compared with the other risk factors. Other important project delay risks in TBM tunnel projects can be listed as; design reviews, late project start, TBM mechanical design review, cutterhead design detail, geotechnical design, TBM stuck, TBM damage, equipment/building rehabilitations.

In the second perspective, the strategies developed for the BBN Tunnel tool are evaluated. The results of case study projects and expert elicitation sessions revealed that, among the suggested risk handling strategies as also given in Section 8.1; design revisions, provides one of the most feasible strategies to decrease project delay durations.

These findings provided valuable information in terms of; determining the critical risk factors for delays and evaluating the most feasible risk mitigation strategies for tunnel projects. In light of the methodology provided in this thesis, similar tools can further be developed considering different objectives, preferences and strategies of companies.

9.3. MAIN CONTRIBUTIONS OF THE RESEARCH TO THE THEORY

Risk assessment methods in tunnel projects generally possess limitations in providing a comprehensive identification of risks that are involved in these projects, modelling causalities between several risk sources, aggregating their effect on each other, identifying and understanding the effect of different risk mitigation strategies on project delay and implementing a comprehensive risk assessment methodology facilitated by a decision support tool. A detailed analysis of these limitations has been provided in Chapter 3.

Therefore, in light of the previous research on the subject and the developed methodology, the thesis provides the following new contributions to the field;

- A novel methodology for project risk assessment for TBM tunnel projects incorporating Bayesian Networks.
- An original and practical risk assessment model that includes a risk taxonomy specific for tunnel projects and risk assessment method that considers interdependencies between risk factors.
- It demonstrates how the methodology can be implemented in a construction company for strategic risk assessment.
- It demonstrates how BBNs can be developed and validated by designing effective expert knowledge elicitation protocols and processes.
- A decision support tool is developed for strategic risk assessment and delay prediction in TBM tunnel projects that can be used to formulate effective risk mitigation strategies to minimize delay in tunnel projects considering the cost of strategies as well as their impact on delay.

As mentioned in Chapter 2, the risk assessment methods suggested in the literature mainly focus on a specified risk event which limits the extent of their utilization. The research developed in this thesis aims to provide a comprehensive method to assess risks in tunnel projects. In order to accomplish this, the research has been developed in a real tunnel construction company. The Company contributed in data and knowledge acquisition processes throughout the research. Using the information gathered from the company case study projects, a risk taxonomy has been developed that contains various risk sources and risk factors that affect delays in tunnel projects.

By conducting numerous expert knowledge elicitation sessions, a BBN model has been created to analyze risks and predict delays, finally risk mitigation strategies has been determined to reduce the impact of these risks. As a result of these processes, the developed research proposed a strategic delay risk assessment methodology for tunnel projects. The methodology is realized in six consecutive phases; 1) Research design, 2) Risk taxonomy, 3) Computational model, 4) Decision support tool, 5) Validation of the model and the BBN Tunnel tool, 6) Implementation of real case tunnel projects.

The computational model corresponds to a BBN based delay risk assessment model which utilizes the advantages of Bayesian networks. The model provides a network structure of tunnel risks considering their correlations. The interdependencies between risk factors have been induced by determining their conditional dependencies. Thus, the developed BBN model can calculate the effects of risk factors on each other and automatically aggregate diverse risk factors to the final project risk. Additionally, the learning aspect of the developed model enables inputting new evidences into the model and updating it according to new information as well as revising it for other tunnel types and companies.

The decision tool on the other hand, allows automatic calculation of the delay risk by engaging the BBN risk assessment model, retrieving the results of the analysis, providing different risk mitigation strategies and providing comparative calculation of the results and cost impacts of these strategies. This enables determining the expected delay durations as well as the results of adopting certain risk mitigation strategies. Therefore, the method suggests a strategic risk assessment process and enhances the quality of decision-making procedures. The system could be used both during the design and construction phases to examine the risk exposures and measures to reduce these risks.

To summarize, the developed risk assessment methodology promotes two aspects: a delay risk analysis model based on Bayesian Belief Networks and a risk mitigation decision support tool based on strategic risk assessment concepts. When combined, the developed methodology allows identifying the expected delay durations and evaluating “feasible” strategies for tunnel projects.

9.4. EXPECTED BENEFITS FOR TUNNEL CONSTRUCTION PROJECTS

As explained in the thesis, the research has been carried out in a construction company. Therefore, company specific data and case study projects have been used throughout this thesis. In order to examine the risk assessment methods adopted in actual tunnel projects case study reports have been evaluated by the researcher and findings have been discussed with Company experts. In light of these, it was seen that the current methods carry out simple probability-impact matrix calculations and neglect the correlations between different risk factors. They also do not examine the impacts of different risk mitigations strategies and utilize decision support tools.

Therefore, the developed risk assessment methodology and BBN Tunnel decision support tool aims to enhance the project risk assessment practices employed in the industry as a result of the following benefits;

- Creation of a comprehensive risk taxonomy for tunnel projects,
- Development of a risk assessment methodology,
- Computerization of project risk assessment process for tunnel project,
- Testing risk mitigation strategies to reduce impacts of delay risks in tunnel projects,
- Development of a decision support tool,
- Facilitation of a decision-making mechanism in the delay risk assessment practice.

In current practices the risk assessment procedures used terms with mixed interpretations, thus clear identification of the related terms possessed an important initial step. Thus, the research methodology developed in this study starts with the identification of principle risk management concepts. Additionally, most risk assessment methods concentrate on specific problems. Therefore, through case study and literature research, an extensive risk taxonomy is created. The taxonomy created here provides detailed information for risks in tunnel projects, involving various parties with a complete structure of interrelations and can be used as a basis for building various risk assessment models for tunnel projects. Based on the empirical and theoretical data, the research specifies various risks in relation with; geological surveys, geotechnical risks, safety measures, design details, country conditions, employer and contractor issues, as well as knowledge, technology and workmanship components in tunnel construction projects. The computerized risk assessment model developed in this study, provides automatic aggregation of interdependencies between diverse risk events that are organized in a BBN structure. The system developed in the research is based on the experiences of practitioners that have been involved in various national and international projects. Instead of the intuition based or independent calculation processes utilized in current practices, the developed computerized risk assessment method enables prediction of delay in a quantitative system. It combines historical and probability information and calculates delay durations. The outcome in implementing any change to the problem can be observed by entering input values into the model. Therefore, the created framework is expected to be useful for tunnel practitioners to predict delay, starting from the design phase until the construction is completed due to the model's ability to update in light of the newly acquired information.

Current decision-making methods in practice are highly insufficient in terms of performing a structured procedure (Han and Diekmann, 2001). Thus, a novel decision support tool is created in this study to provide a computerized project evaluation mechanism. The tool provides remote operation of the risk assessment process by its data input interface that communicates directly with the BBN model. Thus, practitioners can use the tool for directly calculating the project time overrun risk. They can assess both the probabilities of various delay durations as well as a resultant expected delay for their tunnel projects. The study also aims to incorporate the strategic thinking with the computerized model. In order to do that, the BBN model has undergone sensitivity analysis and strategy assessment procedures together with the presence of experts. The tool created in this study incorporates the outputs obtained from the sensitivity analysis of the created computer model and strategy assessment concepts. Post project information have also been used to identify the components critical for delays in tunnel projects. The resultant components identified are used to determine helpful risk mitigating strategies. These strategies aim to enable practitioners to evaluate the risk/return of each strategic option, improve understanding the problems in tunnel projects and thus make better decisions for future circumstances. Furthermore, cost impacts of each strategy has been included. When these aspects are combined, the developed decision support tool enables practitioners to calculate the expected delay durations in their projects, judge between different strategies and identify the most feasible option to reduce delays in tunnel projects.

Through the developed methodology, the practitioners can identify critical project risks, perform quantitative risk analysis, examine the contributions of different risk mitigation strategies and predict the most feasible strategies for minimizing risk. Following the processes proposed in this thesis, similar tools can further be developed considering different objectives, preferences and strategies of companies by following the process proposed in this thesis. Therefore, this research creates a clear and comprehensive framework for risk assessment and a formal project risk evaluation procedure.

To implement the developed methodology in tunnel projects, a roadmap is provided below for the companies that desire to carry out the proposed risk assessment procedure.

1. First, the delay risk taxonomy developed in scope of this thesis should be evaluated. In case the risk taxonomy is found suitable, it can be used otherwise a tailor-made taxonomy could be developed by the company.

2. Then, using this risk taxonomy, the BBN model should be assessed. If the network structure is found adequate, the BBN model developed in this research can directly be utilized. If the company finds it necessary to adjust the relations, eliminate or add some risk events, the BBN model should be revised. In this case, CPTs should also be modified.
3. After the required data is entered into the model, risk mitigation strategies shall be developed. This can be achieved by examining the strategies determined in this research and carrying out the same procedure (i.e. strategic risk assessment) to identify additional ones.
4. In the final step, the decision support tool should be developed to suit the requirements of the decision makers in the risk handling processes. The tool developed in this thesis provides predicting delays and assessing the impacts of different risk mitigation strategies. In addition to these, companies can integrate other decision-making perspectives into the tool.

It should be noted that to carry out these consecutive steps, whenever a data that is provided in this research is found unsuitable (model provided in the research can be too detailed or should be modified according to project properties or company strategies), then the data involved in that stage shall be adjusted to suit the needs.

For instance, in an NATM project, the risk taxonomy accomplished in this research may contain risk factors that are not relevant for the project and certain nodes in the BBN model may not be required or changed. In this case, the risk taxonomy and the BBN model should be revised together with the CPT assignments for the relevant relations. After that, strategy determination in step 3 and revising the decision support tool can be done. As a result, using the developed generic methodology and this sequential revisal procedure, a problem specific BBN delay risk assessment model and decision support tool will be provided for any company who wants to implement this method in different types of projects.

It should also be noted that the data gathering procedures required during these steps should involve building expert teams that have suitable backgrounds in tunnel projects. These expert teams should collaborate in each of these steps, through extensive expert knowledge elicitation sessions.

9.5. LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORK

There have been efforts both in the literature and in practice for assessing risks in tunnel projects, however, these methods possessed certain drawbacks especially in terms of providing a comprehensive approach and decision support for delay risk assessment. This study has advanced the knowledge on the risks involved in tunnel projects through an extensive risk taxonomy and proposed a systematic and novel delay risk assessment methodology using BBNs. The delay prediction algorithm is further used to develop a decision support tool that can be utilized for selection of cost-effective strategies to minimize delay.

Following are identified as major limitations of this research and potential areas for further research:

- First, it should be noted that; the computational model has been developed in combination of literature review findings and utilizing expert knowledge elicitation methods to collect information from experts in a construction company. The model represents invaluable expert judgements in the tunnel construction field. However, as the findings reflect opinions of experts from a single construction company, findings cannot be generalized. The generic methodology proposed in this thesis can be used to develop similar models and tools for different companies.
- One of the difficulties faced during this study was defining correlations between risks in the BBN model which involved identification of numerous interrelations using multi-dimensional CPT tables. Although managing such a process provided creating a comprehensive model, it is seen that the time required for the experts to

understand the effect of each parent node to the child node increases substantially as the relations become more interconnected. The software that is used in modeling also had limited capabilities in terms of visualization of dimensions in CPTs. Therefore, the practitioners that aim to develop similar models may rather prefer to separate the model into sub-models. Then the results of each leaf node in the sub-model can be combined to reach the analyzed risk consequence. Moreover, visualization tools can be developed to facilitate this process.

- The tool has been developed in collaboration with the construction company which means that expectations from the tool were shaped by company experts and information fed into the tool reflect a single company's experience. Therefore, it should be emphasized again that the tool and embedded strategies are company-specific and cannot be generalized. Similar tools can further be developed considering different objectives, preferences and strategies of companies by following the process proposed in this thesis.
- A further research area can be development of similar tools considering different types of tunneling technology, such as NATM. It would be interesting to utilize the developed methodology for NATM projects, compare the network structure and the results of the risk assessment method.
- Additionally, as the developed methodology targets evaluating the delay risks in tunnel projects, it would be also beneficial to use the same methodology for the cost overrun perspective. The risk factors for cost risks can either be implemented through the BBN model development stage or through creating a cost overrun risk assessment decision support tool using the methodology provided in this thesis.
- Finally, the benefits and bottlenecks about the methodology proposed and the tool developed should be monitored to understand its impact in practice. There are several tools proposed in the literature that are claimed to facilitate the decision-making processes in companies. However, there are limited number of follow-up studies that report findings of practical applications. A comparative study can be conducted considering a real project at early stages of development first by using traditional risk assessment methods and then using the proposed method. Then,

benefits such as improvements during the decision-making process, prediction capability, confidence in decisions etc. can be reported.

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APPENDICES

A. Example for calculation of conditional probabilities through BBNs

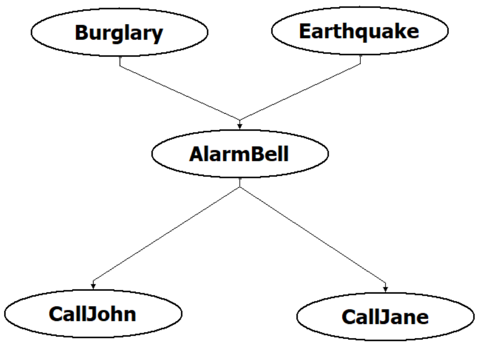

Figure 0.1. Example BBN

In this example it is assumed that the house has a burglar alarm system, in which when the alarm rings friends John and Jane are notified. This automatic call system is created by the alarm company however was not guaranteed to function all the time. Additionally, as the house is located in a seismically active area, the alarm also rings occasionally when an earthquake happens. After the DAG is created as in Figure A.1, the CPTs are assigned to each node according to the statistical data obtained from the alarm company (Table A.1). The number of parameters for this particular two-stated example is 25=32.

The probability P(A\b,e) also known as the probability distribution of alarm ringing consists of two states P(A) denoting the positive state whereas P(a) denotes the negative state. According to this notation probability that the alarm rings P(A) can be calculated as;

P(B)*P(E)*P(A\BE)+P(b)*P(E)*P(A\bE)+P(B)*P(e)*P(A\Be)+P(b)*P(e)*P(A\be) = 0,25%

Table 0.1. *CPT Assignments of the Example BBN*

P (Burglary)	
yes	no
0,001	0,999

P (Earthquake)	
yes	no
0,002	0,998

Parent Nodes		P(AlarmBell)	
P(Burglary)	P(Earthquake)	yes	no
yes	yes	0,95	0,05
	no	0,94	0,06
no	yes	0,29	0,71
	no	0,001	0,999

Parent Node	P (CallJohn)	
P(AlarmBell)	yes	no
yes	0,90	0,10
no	0,05	0,95

Parent Node	P (CallJane)	
P(AlarmBell)	yes	no
yes	0,70	0,30
no	0,01	0,99

The probability that there is a burglary when John and Jane both give a call P(B\J,J) can be calculated as follows;

P(B)*P(E)*P(A\BE)*P(John\A)*P(Jane\A)+P(B)*P(E)*P(a\BE)*P(John\a)*P(Jane\a)+P(B)*P(e)*P(A\Be)*P(John\A)*P(Jane\A)+P(B)*P(e)*P(a\Be)*P(John\a)*P(Jane\a)=0,059%

On the other hand, P(b\J,J) is calculated as;

P(b)*P(E)*P(A\bE)*P(John\A)*P(Jane\A)+P(b)*P(E)*P(a\bE)*P(John\a)*P(Jane\a)+P(b)*P(e)*P(A\be)*P(John\A)*P(Jane\A)+P(b)*P(e)*P(a\be)*P(John\a)*P(Jane\a) =0,15%

Therefore P(b\J,J) = (0,00059;0,00149) and after normalization, P(b\J,J) = (0,28;0,72).

B. Risk factors from theoretical research

Table 0.2. *Tunnel construction risks from literature survey*

Reilly (2000)	Luu et al. (2009)	Cardenas et al. (2014)	Nezarat et al. (2015)
Tunnel Projects	**Construction Projects**	**Tunnel Projects**	**Tunnel Projects**
Injury or catastrophic failure with the potential for loss of life and personal injury	Owner's financial difficulties, Delays in progress payments by owners, Contractors' financial difficulties	Face instability in soft soils when using slurry shields, Face instability in soft soils when using an earth pressure balance shield	Groundwater inflows, Gas emissions
Extensive material and economic damage, and loss of credibility for those involved	Inappropriate construction methods, Inadequate contractors' experience, Lack of capable owners/project managers	Collapse and large deformations in shaft excavations, Collapse and large deformations of excavations for cross-passages in soft soils	Face tunnel instability, Instability of tunnel wall
Significant increases in project and support costs	Low awarded bid prices, Material price fluctuations, Shortage of equipment, Shortage of materials	Excessive deformation, damage, and leakage of concrete lining	Mixed ground conditions, Clogging of clay
Not meeting functional design, operational, maintainability and quality standards	Designers' inadequate experience and capability, Lack of capable and responsible site supervisors, Defective works and reworks	Excessive volume loss leading to surface settlements in tunnels bored in soft soils	Swelling of rocks, Squeezing
Delay of project completion	Slow site handover, Owners' site clearance difficulties, Inclement weather		

C. Risk registers for tunnel construction projects

Table 0.3. *Tunnel construction risks from literature survey*

Risk Cluster	Risk Event
TBM Tunnel & TBM Advance Rates	Damage to TBM cutterhead
	Incorrect cutterhead design
	Clogging of TBM Cutterhead
	Power supply delay
	Inability to correct TBM Misalignment / Operator caused deviation from planned tunnel alignment
	Combination of hard, massive and abrasive rock increases wear of the cutter tools
	Breakdown of equipment leaves face unsupported for longer than natural stand up time
	Delays in obtaining materials and spare parts for equipment repair
	Thicker than expected zones of altered material in fault zones
	Non –continuous mining through fault zones
	Inadequate stand up time allows material to ravel at a faster rate than can be supported

TBM Tunnel & TBM Advance Rates	TBM Procurement risk, Using second hand TBMs
	Wrong selection of TBM
	Late delivery of the TBM delays start of tunneling
	Logistical difficulties and volume of muck disposal, Utilization of TBM Muck and Rehabilitation of excavated material from TBM (soil mixed with foam) due to environmental issues, Rejection of muck at final disposal site and owner rejects temporary storage on site
	Insufficient lay down for precast segments slows supply to the tunnel
	Inability to support planned excavation rate at the work shaft site due to logistical challenges
	Finding archaeological artefacts
	Rehabilitation of Existing Buildings
	Impact on Existing Structures: Going under existing railway, clash with existing concrete structure, going under shallow foundations of existing old buildings
	Unexpected Noise and Vibration Level
	Insufficient power and or torque on the TBM, Loss of power including lighting and ventilation
	Failure to identify buildings or structures or utilities or infrastructures important to life-safety which may be impacted by TBM construction, or identify the magnitude of the impact

TBM Tunnel & TBM Advance Rates	Alignment conflicts with or is close to existing underground structure or cavity or old well
	Ground instability, loss of slurry/face pressure
	Damage to existing buildings (tunneling, stations, surface heave due to high EPB pressure etc.)
	Incompatibility of TBM design and tunnel lining design
	Cracking of the lining
	Segment quality is below requirements
	Early deterioration/leakage of segments
	Collapse or excessive deformation of linings approaching the tunnel
	Face stability (sand pockets, sand lenses, transition from sand to clay etc.)
	Unskilled TBM operator
	TBM failure to be commissioned or operate reliably, or as required or planned
	Segments slip or fall during erection causing damage or injury
	Wear and tear of slurry pipeline and slurry treatment plant (STP) slows progress
	Slurry pipeline failure causes inflow of slurry into tunnel

NATM Tunnel	Delay in delivery procurement, fabrication, and assembly of liner formwork
	Alignment conflicts with or is close to existing underground structure or cavity
	Finding archaeological artefacts
	Rehabilitation of Existing Buildings
	Impact on Existing Structures: Going under existing railway, clash with existing concrete structure, going under shallow foundations of existing old buildings
	Unexpected Noise and Vibration Level
Cut-and-Cover Constructions	Delay in getting permits to start cut and cover excavation and or wrong assumptions on excavation rates delays start of tunneling
	Incompatibility between design assumptions and construction methods
	Unknown utility relocations required at portals and toll booths
	Changing from bottom up to top down (increase in cost of excavation)
	Changing top deck construction method from cast in situ to precast

Geotechnical Conditions	Unforeseen Geological/Geotechnical condition
	Failure to adequately predict, monitor or respond to ground deformation
	Different soil conditions than in geological study/ Unexpected geological conditions
	Facing boulders/rocks on the way of TBM / Non continuous tunnel boring
	Earthquake induced liquefaction during construction leads to failure of utilities and power supply and TBM settlement if in sandy lenses
	Market risk for D-Wall (hydro fraise) machine
	Gouge material in the faulted zones contain higher than expected clay content
	Difficulty in achieving effective pre-excavation treatment (i.e. grouting) in unstable ground
	Quality of fill could be problematic for the construction of the D wall
	Failure to adequately predict, monitor or respond to ground deformation
	Over-confidence in the method or ground conditions
	Excessive settlement of structures or buildings
	Low overburden and face instability and support of overburden materials

Geotechnical Conditions	Tunnel instability – rock falls, face collapse
	Local collapse leads to progressive collapse of extensive area of the works
	Flooding of the tunnel
	Incompatibility between design assumptions and construction methods
	Seepage of flammable liquid/vapor into tunnel
	Excavation blast in competent rock travels into unstable material or fault zones
	Large or uncontrolled over break
	Low rock stresses or poor confinement of the rock above tunnel axis require more than anticipated pre-bolting (spilling)
	Crushed or blocky rock from the face, or walls and roof close to the face before proper rock support has been installed
	Seepage of flammable or noxious liquid/vapor into excavation
	Failure to adequately predict, monitor or respond to ground deformation
	Excavation reveals archeological findings
	Alignment conflicts with or is close to existing underground structure or cavity

Electro-mechanical Systems	Inadequate estimation of patronage demand
	Assessment of emergency scenarios require the re-design of tunnel or station structures
	Absence of railway operator, interfacing contractors or equivalent representation
	Interface problems with other Parties in the neighborhood
	Inadequate interfacing/coordination with external interfaces
	Possibility non-integration of the systems (i.e. SIMS-SCADA) Lack of timely management of software development process
	Inadequate planning and management of the integrated commissioning program
	Unexpected revisions due to system level integration and impact of optimizations (i.e. headway not reached, change of turnout shaft locations etc.)
	Additional measures for fire protection that is not foreseen during tender
	Delays caused by other Parties' slow utility relocation activities
	Delays in authority approvals
	Absence of storage area for onboard equipment
	Dust suppression and tunnel ventilation requirements much higher than anticipated to control the high levels of quartzite dust to safe level during mining

Construction Risks	Incorrect Time Estimates / Time Extension
	Scope changes from third party stakeholders
	Employer’s decision-making delay / Additional Employers requirements
	Claims/Fines due to design changes such as increasing tunnel inner diameter
	Change of project delivery times due to the political decisions/ Political Changes
	Local or Global Economic Crisis
	Permits and Approvals
	Site Access Delays
	Acceleration Work Program: cash flow, design changes problems
	Payment delays
	Sub-contractor defaults or under-performs, Failure of sub-contractors delays the project
	Bankruptcy of Subcontractors
	Lump Sum Pricing to Subcontractor
	No Escalation - Inflation Risk

Construction Risks	Environmental constraints, Unexpected utilities that is not foreseen in data received from local authorities
	Problems with the concrete supplier
	Logistic Difficulties
	Problems in customs clearance
	Material damage/loss during transportation and handling or poor storage conditions
	Lack of coordination between parties, internal and external
	Delay in transportation
	Foreign Country - Unknown Country Risk
	Incorrect Cost Estimates
	Local currency vs. foreign exchange rate/Escalation of Prices every 3 months as per contract
	Insufficient availability of skilled labor crews, Inexperience of workforce, Unexpected manpower cost
	Difficulty to provide material & equipment
	Interfacing works are delayed

D. Risk taxonomy questionnaires

Table 0.4. *Risk taxonomy questionnaire*

TBM ADVANCE RATE	IMPORTANCE Expert 1	IMPORTANCE Expert 2
Unexpected Problems in TBM Procurement / Late Delivery of TBM		
TBM Procurement Method (ownership/renting/refurbishment)		
Delay in Mantling of TBM		
Number of TBM machines		
Delays in Getting Permits to Start TBM Works		
Wrong Assumption of TBM Advance Rates		
Loss of Power to TBM		
Breakdown / Damage of TBM		
Wear of the Cutter tools		
Availability of Precast Concrete Segments when Needed		
Slurry Pipeline Failure		
Unskilled TBM Operator		
Operator Caused Deviation from Planned Tunnel Alignment		
Non–continuous Boring through Fault Zones		

Collapse or Excessive Deformation of Linings Approaching the Tunnel		
Finding Archaeological Artefacts		
Alignment Conflicts with Existing Underground Structure / Cavity		
Utility Relocations that is not Foreseen in data received from authorities		
Damage to Existing Buildings		
Logistical Difficulties and Volume of Muck Disposal		
TBM / TUNNEL DESIGN	**IMPORTANCE Expert 1**	**IMPORTANCE Expert 2**
Type of TBM machine		
Wrong Selection of TBM Type		
Delay in Getting Permits to Start Cut and Cover Excavation		
Vague/Undetailed TBM Design		
Change Requirement in Tunnel diameter/Construction method		
Claims due to Design Changes such as Increasing Tunnel Inner Diameter		
Vague/Undetailed Tunnel Lining Design		
Vague/Undetailed Cutterhead Design		

Identification of Buildings, Structures, Infrastructures Important to TBM Alignment and Construction Safety		
Segment Quality is Below Requirements		
Incompatibility Between Design Assumptions and Construction Methods		
Unexpected Revisions due to System Level Integration and Impact of Optimizations (i.e. headway not reached, change of turnout shaft locations etc.)		
Assessment of Emergency Scenarios Require the Re-design of Runnel or Station Structures		
Tunnel not Designed to Appropriate Blast Loading from Terrorist Threat		
GEOTECHNICAL DESIGN	**IMPORTANCE Expert 1**	**IMPORTANCE Expert 2**
Vague/Undetailed Geological Report		
Different Soil Conditions than in Geological Study/ Unforeseen Geological Conditions		
Facing Boulders/Rocks on the way of TBM		
Thicker than Expected Zones of Altered Material in Fault Zones		
Face Stability (sand pockets, sand lenses, transition from sand to clay etc.)		
Tunnel Instability – Rock falls, Face collapse		

Over-confidence in the Method or Ground Conditions		
Difficulty in Achieving Effective Pre-excavation Treatment (i.e. grouting) in unstable ground		
Quality of Fill is Problematic		
Earthquake Induced Liquefaction during Construction Leads to Failure of Utilities and Power supply and TBM Settlement if in Sandy Lenses		
Excessive Water Ingress into Tunnel during Construction		
TUNNEL CONSTRUCTION	**IMPORTANCE Expert 1**	**IMPORTANCE Expert 2**
Length of Tunnel		
Tunnel Construction Passing from Urban Area		
Noncontinuous Tunnel Boring		
Loss of Power, Including Lighting and Ventilation		
Excavation Blast in Competent Rock Travels into Unstable Material		
Large or Uncontrolled Overbreak		
Local Collapse Leads to Progressive Collapse of Extensive Area of the Works		
Dust Suppression and Tunnel Ventilation Requirements Much Higher than Anticipated to Control the High Levels of Dust to Safe Level During Mining		

Additional Measures for Fire Protection that is Not Foreseen During Tender		
Finding Archeological Artefacts		
Alignment Conflicts with or is Close to Existing Underground Structure or Cavity		
Unexpected Utility Relocations that is not Foreseen in Data Received from Local Authorities		
Damage to Existing Buildings (tunneling, station excavations, surface heave due to high EPB pressure etc.)		
Unexpected Noise and Vibration Level		
Tunneling Beneath Vibration Sensitive Buildings such as the Hospital Causes Environmental Issues		
Flooding of Shaft during Construction Due to Storm Surge		
CONSTRUCTION	**IMPORTANCE Expert 1**	**IMPORTANCE Expert 2**
Duration of construction		
Incorrect Time Estimates and Risk of Time Extension		
Scope changes from Third Party / Stakeholders		
Difficulty in Getting Construction Power to Site		

Site Access Delays		
Additional Road Relocation Works Mentioned in Land Development		
Delays in Permits and Approvals		
Foreign Country - Unknown Country Risk		
Problems in Customs Clearance		
Change of Project Delivery Times due to Political Changes		
Delays in Logistics / Transportation		
Procurement Delays of Materials & Equipment		
Material damage/loss during Transportation		
Project Budget		
Financial size of the Contractor Company		
Sub-contractor Defaults or Under-performs		
Experience of Contractor in Similar Tunnel Construction Works		
Experience of Workforce		
Insufficient Availability of Skilled Labor Leading to Unexpected Manpower Cost		

Environmental Constraints / Community Objection to Construction Works		
Risk of Rehabilitation Requirement for Existing Buildings		
TUNNEL SAFETY	**IMPORTANCE Expert 1**	**IMPORTANCE Expert 2**
Breakdown of Equipment Leaves Face Unsupported for Longer than Natural Stand Up Time		
Collapse, Cracking or Excessive Deformation of Linings Approaching the Tunnel		
Segments Slip or Fall During Erection Causing Damage or Injury		
Inflow of Slurry into Tunnel due to Slurry Pipeline Failure		
Tunnel Instability – Rock Falls, Tunnel Collapse		
Dust Suppression and Tunnel Ventilation Requirements Much Higher than Anticipated to Control the High Levels of Dust to Safe Level During Mining		
Damage to Existing Buildings (tunneling, station excavations, excessive		
Earthquake Induced Liquefaction During Construction		
Flooding of the Tunnel		
Seepage of Flammable or Noxious Liquid/Vapor into Tunnel		

Fire in Tunnel		
Tunnel not Designed to Appropriate Blast Loading from Terrorist Threat		
EMPLOYER	**IMPORTANCE Expert 1**	**IMPORTANCE Expert 2**
Additional Employer Requirements/Work Acceleration Demand		
Scope Changes from Third Party Stakeholders		
Payment Delays		
Bankruptcy of Subcontractors		
Failure of Subcontractors or Under-performs		
Insufficient Availability of Skilled Labour Crews		
Logistical Difficulties and Volume of Muck Disposal		

E. Delay risk taxonomy

Table 0.5. *Taxonomy of Tunnel Projects Delay Risk*

Risk Events	Risk Factors	Risk Consequences
Detail of Geotechnical Design	Explosive Gas Leakage into Tunnel	Damage to Equipment and Buildings, H&S Issues, TBM Stoppage, Decrease in TBM Advance Rate
	Unexpected Ground Conditions	
	Detail of Ground Surveys	
	Effectiveness of Soil Improvement before Excavation	
Detail of Tunnel Design	Unexpected Alignment Revisions	Design Review, Segments Damage, Equipment Damage
	Segments Geometric Design not Meeting Project Requirements	
	Inconsistency Between Design Assumptions & Construction Method	
	Change in Construction Methods (from TBM to NATM)	
Detail of Cutterhead Design	Mechanical Design not Meeting Project Requirements	Damage to Equipment, TBM Stoppage
	Damage to Cutterhead	
Contractor's Experience	Overconfidence in Construction methods	Decrease in TBM Advance Rate, Damage to Surrounding Structures
	Health and Safety Issues	

Place of Construction	Capacity of Segment Storage Area	Delays in Operations
	Late Site Access	Late Start
	Different Circumstances Compared to Data from Authorities	Late Start, Delays in Operations, Decrease in TBM Advance Rate
	Tunneling below Historic Artefacts	
	Type of TBM Machine	
Project Duration	Number of TBM Machines	Delays in Operations, Design Review
	Employer’s Additional Requirements	
Experience of Workers	Experience of TBM Operator	Late Start, Delays in Operations
	Performance of Segment production Sub-Contractor	
Country of Construction	Delays in Site Access	Late Start, Delays in Operations
	Delays in Advance Payment	
	Delays in Material Supply	
	Material Loss during Transportation	
	Delays in Progress Payments	
TBM Procurement Method	Delays in TBM Procurement / Delays in TBM Assembly	Late Start
	Delays in Customs Clearance	

F. BBN Tunnel model on MSBNx

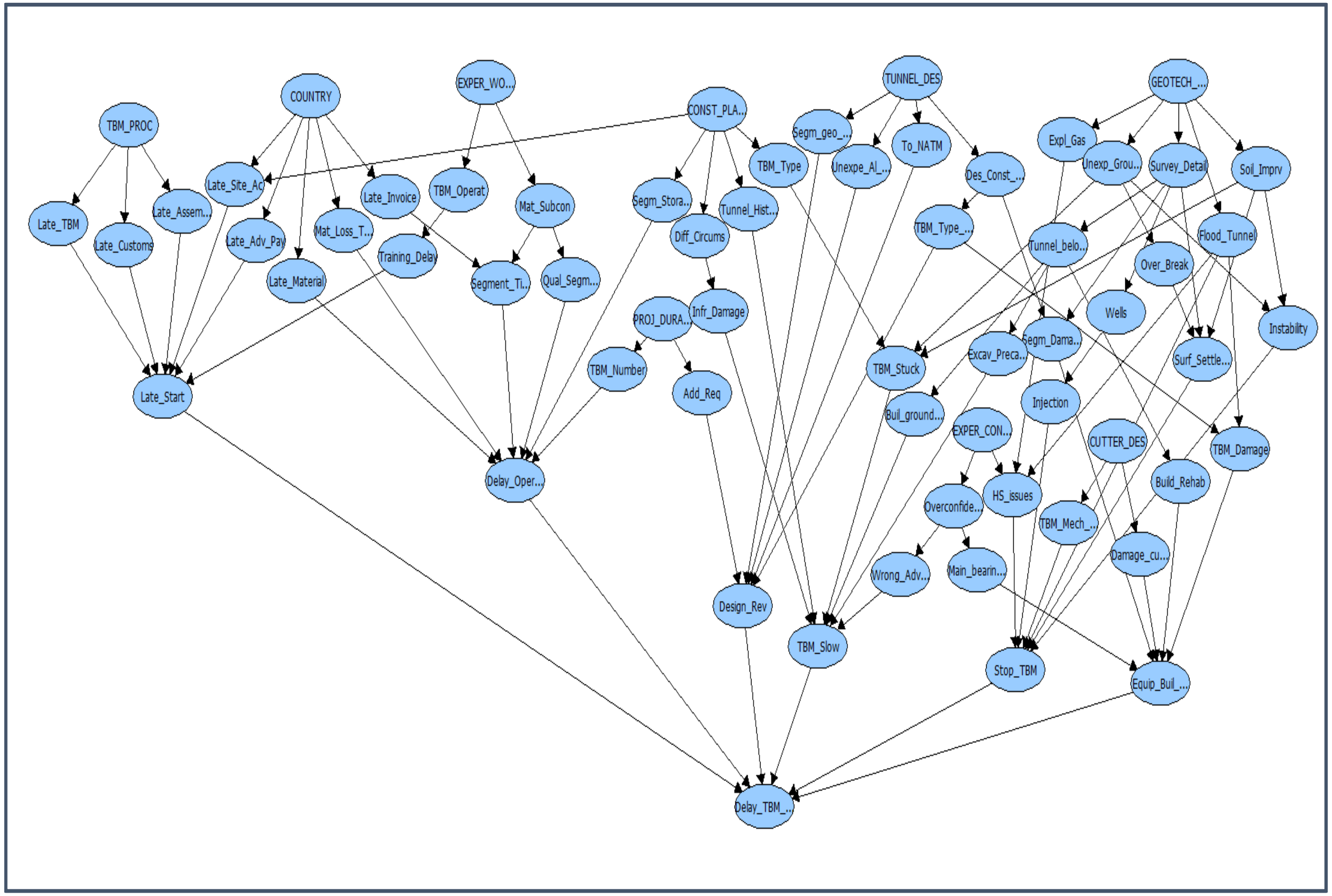

Figure 0.2. The BBN based risk assessment model

G. Data registry for Session 4

Table 0.6. *Data registry form for session 4*

	Risk Factors	States		
1	**EXPERIENCE OF WORKERS/ SUBCONTRACTORS**			
1.1	Qualification of Material Sub Contractors			
	Segments material quality			
	Segments production time			
1.2	Qualification of TBM operator			
	Training Delay			
	DELAYS IN OPERATIONS			
2	**COUNTRY CONDITIONS**			
2.1	Delays in Invoice Payments			
2.2	Delays in Advance Payment			
2.3	Delays in Site Access			
2.4	Delays in Material Supply			
2.5	Material Loss during Transportation			
3	**PROCUREMENT METHOD OF TBM**			
3.1	Delay in TBM Supply			
3.2	Delay in Customs			
3.3	Delays in TBM Assembly			
	LATE START			
4	**DURATION OF PROJECT**			
4.1	Employers Additional Requests			
4.2	Number of TBM			
5	**DETAIL OF CUTTERHEAD DESIGN**			
5.1	Revisions required in Mechanical design of TBM			
5.2	Damage to the cutter disks			
	EQUIPMENT/BULDING DAMAGE			

6	**CONTRACTORS EXPERIENCE IN SIMILAR TUNNEL WORKS**			
6.1	Overconfidence in Constr. Methods			
	Wrong Assump. of TBM’s Advance Speed			
	Main Bearing Damage			
6.2	Health and Safety Isuues			
7	**DETAIL OF GEOTECHNICAL DESIGN**			
7.1	Unexpected Ground Conditions			
	Over/ Unexpected Breaking			
	Tunnel Instability			
7.2	Ground Impr. before Excav. cannot be done effectively			
	Tunnel Instability			
	Surface Settlements			
7.3	Flooding of Tunnel			
7.4	Leakage of explosive gas into tunnel			
7.5	DETAIL OF SITE SURVEYS			
	Surface Settlements			
	Damage to the Segments			
	Excavation below Vibration Sensitive Buildings/ Underground Structures			
	Excavation Precautions during Tunneling			
	Building ground improvements			
	DESIGN REVISIONS			
	TBM SLOW DOWN			
	STOPPAGE OF TBM			
	Detection of Wells			
	TBM Damage			
	Filling the wells with concrete injection			

8	**PLACE OF CONSTRUCTION**			
8.1	Type of TBM			
8.2	Conditions different than data taken from local authorities			
	Unexpected Infrastructure Displacements			
8.3	Tunnel facing Historic Artefacts			
8.4	Segment Storage Area			
9	**DETAIL OF TUNNEL DESIGN**			
9.1	Unexpected Alignment Revisions			
9.2	Segments Geometric Design Revisions			
9.3	Inconsistency between design assumptions & construction methods			
	Wrong selection of TBM Type			
	TBM Stuck			
9.4	Change in Construction Methods (from TBM to NATM)			
	DELAY TBM TUNNEL			

H. States of the BBN based Risk Assessment Model

Table 0.7. *States of the BBN based Risk Assessment Model*

BBN Node	States
TBM PROCUREMENT	
TBM Procurement Method	Purchase: Acquisition of TBM Machine from the manufacturer, involves design of the machinery by the manufacturing firm Refurbishment: Revision of a previously owned TBM Machine according to the geotechnical conditions of the project
LATE TBM	
Delays in Delivery of TBM Machine/Sub Equipments on Site	Yes No
LATE ASSEMBLY	
Late Assembly of TBM Machinery on Site	Yes No
LATE CUSTOMS	
Delays of TBM Machinery/Sub Equipments in Customs Clearance	Yes No
COUNTRY	
Country of the Construction with regards to the Contractor	International: The tunnel construction project is not on the country of the Main Contractor National: The tunnel construction is on the country of the Main Contractor
LATE SITE ACCESS	
Delays in Contractor's Site Access	Yes No
LATE ADVANCE PAYMENT	
Delays in Client's Advance Payments in Project Start	Yes No

LATE MATERIAL	
Delays in Segment Production Material Supply	Yes /No
MATERIAL LOSS TRANS.	
Loss of Segment Materials during Transportation to Site	Yes /No
LATE INVOICE	
Delays in Client's Interim Payments during Construction	Yes /No
EXPERIENCE WORKERS	
Experience Level of TBM Operator and Segment Production Workers	Semi-experienced Experienced
TBM OPERATOR	
Experience of the TBM Operator	Poor-qualified Qualified
TRAINING DELAY	
Delay Requirement of the TBM Operator prior to Project Start	Yes /No
MAT. SUBCONTRACTOR	
Performance of Segment Production Sub-Contractor	Low-performance Adequate
QUALITY SEGMENTS	
Quality of Segments for Tunnel Operations	Not-adequate Adequate
SEGMENT TIME	
Rate of Segment Production compared to Advancement of Tunnel Boring	Slower than TBM Fits TBM

SEGMENT TIME	
Rate of Segment Production compared to Tunnel Advancement	Slower than TBM Fits TBM
<u>CONST. PLACE</u>	
Place of the Tunnel Construction in terms of Surface Access	Urban: Tunneling is carried out where surface access is greatly limited Terrain: Tunneling is carried out in surface accesible area
SEGMENT AREA	
Sufficiency of Segment Production Area on Site	Not-enough /Enough
DIFFERENT CIRCUMSTANCES	
Different circumstances in Tunnel Alignment than Data Obtained during Design Stage	Yes /No
TUNNEL HISTORIC	
TBM Tunnel Boring meeting any Historic Artefacts	Yes /No
TBM TYPE	
Type of TBM Machine	Slurry EPB Hard Rock-Open Type
INFRASTRUCTURE DAMAGE	
TBM Boring Damages the Infrastructures	Yes /No
<u>PROJECT DURATION</u>	
Estimated Duration of Tunneling Project	18-24 months 24-36 months > 36 months

TBM NUMBER	
Number of TBM Machines	1-2 3-6 7-10
ADDITIONAL REQUIREMENTS	
Additional Employer Requirements during Construction such as Alignment Revisions/Design Changes	Yes /No
TUNNEL DESIGN DETAIL	
TBM Tunnel Design's Detail Level regarding the Tunnel Geometry, Support Systems	Roughly Prepared Adequate Detailed
SEGMENT GEOMETRY REVISION	
Necessity to Change the Segment Geometry	Yes /No
UNEXPECTED ALIGNMENT REVISION	
Necessity to Change the Alignment Design Unexpectedly	Yes /No
TBM to NATM	
Necessity to Change the Tunnel Design from TBM to NATM	Yes /No
DESIGN CONSTRUCTION INCONSISTENCY	
The Construction Conditions do not Meet the Structural Designs	Yes /No
TBM TYPE WRONG	
Type of TBM Machine is Different than the Requirements	Yes /No

EXPERIENCE CONTRACTOR	
Experience of Main Contractor in Similar Projects	Semi-experienced Adequate
OVERCONFIDENCE	
Confidence of the Main Contractor that affect performing Construction Methods with all Precautions	Yes /No
WRONG ADV. SPEED	
Difference between Estimated and Actual TBM Machine Advance Speed	Slower than estimated Close to estimation Faster than estimated
MAIN BEARING DAMAGE	
Damage to the TBM Machine's Main Bearing	Yes /No
GEOTECHNICAL DESIGN DETAIL	
Detail Level of Geotechnical Design	Roughly Prepared Adequate Detailed
UNEXPECTED GROUND CONDITIONS	
Ground Conditions not Meeting the Anticipated Situations	Yes /No
SURVEY DETAIL	
Detail Level of Soil Surveys due to distances of boring intervals	Roughly Prepared Adequate Detailed
SOIL IMPROVEMENTS	
Effectiveness of Soil Improvements During Tunnel Boring	Not Effective Effective

OVERBREAK	
Overbreak of Rock Mass during Tunnel Boring	Yes /No
FLOODING TUNNEL	
Flooding of Tunnel Section due to Excessive Ground Water Leakage	Yes /No
EXPLOSIVE GAS	
Leakage of Explosive Gas into Tunnel Section that is Unexpected or Undetected	Yes /No
TUNNEL BELOW SENSITIVE BUILDINGS	
TBM Tunnel Boring Proceeding Below Vibration Sensitive Buildings such as Hospitals	Yes /No
WELLS	
Meeting Wells that has not been Detected	Yes /No
SURFACE SETTLEMENTS	
Settlement of Surface Structures	Yes /No
INJECTING THE WELLS	
Necessity to inject the Wells with cement mixture to eliminate voids structurally critical in tunnel boring	Yes /No
SEGMENTS DAMAGE	
Structural Damage to Segments	Yes /No
BUIL. GROUND IMPR.	
Necessity to Conduct Ground Improvements to Buildings	Yes /No

EXCAVATION PRECAUTIONS	
Necessity to Construct Additional Excavation Support Systems	Yes /No
H&S ISSUES	
Facing Health and Safety Issues during Tunneling	Yes /No
TUNNEL INSTABILITY	
Instability of TBM Tunnel Structure	Yes /No
BUILDING REHABILITATIONS	
Rehabilitation of Buildings Tunnel overpasses	Yes /No
TBM DAMAGE	
Damage to the TBM Machine during Tunneling	Yes /No
CUTTERHEAD DESIGN	
Detail Level of Cutterhead Design	Roughly Prepared Adequate
TBM MECH. DES. REV.	
Necessity to Revise the TBM Mechanical Design	Yes /No
CUTTERDISK DAMAGED	
Damage to the Cutterdisk during Tunneling	Yes /No
TBM STUCK	
TBM Being Stuck Underground	Yes /No

LATE START	
Delay in TBM Tunneling	0-3 months 3-6 months More than 6 months
DELAY OPERATIONS	
Delay in TBM Operations due to Segment Production and TBM Advancement	0-2 months /2-4 months /4-6 months
DESIGN REVIEW	
Necessity to make Design Revisions	Major /Minor /No
TBM ADVANCE SPEED SLOW	
Rate of slowing down of TBM Advancement compared to Estimated Advancement Speed	Maximum (decrease 50%-70%) Moderate (decrease 25%-50%) Mininmum (decrease to 25%)
STOP TBM	
Duration of TBM Stop during Tunnel Boring	0-2 months /2-4 months /4-6 months
EQUIPMENT REPAIR BUILDING REHAB	
Duration of Equipment Repair and Building Rehabilitations	0-2 months /2-4 months /4-6 months
DELAY TBM TUNNEL	
Delays in TBM Tunnel Boring	Very low (0-4 months) Low (4-9 months) Medium (9-12 months) High (12-18 months) Very High-Extreme (18-24 months)

i. Programming code section of BBN Tunnel

```
'save model
state0 = Math.Round(model.Engine.Belief("Delay_TBM_Tunnel", 0), 4)
state1 = Math.Round(model.Engine.Belief("Delay_TBM_Tunnel", 1), 4)
state2 = Math.Round(model.Engine.Belief("Delay_TBM_Tunnel", 2), 4)
state3 = Math.Round(model.Engine.Belief("Delay_TBM_Tunnel", 3), 4)
state4 = Math.Round(model.Engine.Belief("Delay_TBM_Tunnel", 4), 4)
MODELTableAdapter. InsertQuery ("Current Project", model. ModelNodes. Item(8). States(0). Name, state0, model. ModelNodes. Item(8). States(1). Name, state1, model.ModelNodes.Item(8).States(2).Name, state2, model. ModelNodes. Item(8). States(3). Name, state3, model. ModelNodes. Item(8). States(4). Name, state4)
MODELTableAdapter. Fill(DataSetMODEL. MODEL)
'strategy1
models1. Engine. Evidence. Set (models1. ModelNodes. Item(48). Name, RadDTBM. Text)
models1. Engine. Evidence. Set (models1. ModelNodes. Item(4). Name, RadDCountry. Text)
models1. Engine. Evidence. Set (models1. ModelNodes. Item(13). Name, RadDEOW. Text)
models1. Engine. Evidence. Set (models1. ModelNodes. Item(3). Name, RadDConplace. Text)
models1. Engine. Evidence. Set (models1. ModelNodes. Item(35). Name, RadDDuratProject. Text)
```

models1. Engine. Evidence. Set (models1. ModelNodes. Item(55). Name, RadDTUNDES. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(18). Name, RadDGEO. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(12). Name, RadDMAINCON. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(5). Name, RadDCUTTERHEAD. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(28). Name, RadDLATESTART. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(17). Name, RadDfloodtunnel. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(46). Name, RadDTBMMEC. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(7). Name, RadDDELAYOP. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(45). Name, RadDTBMDAMAGE. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(53). Name, RadDTBMNATM. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(14). Name, RadDEQUIP. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(10). Name, RadDDESIGN. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(0). Name, RadDADDEMPLOYE. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(54). Name, RadDTBMTYPE. Text)

models1. Engine. Evidence. Set (models1. ModelNodes. Item(58). Name, RadDTUNNELHIST. Text)

models1.Engine.Evidence.Set("Survey_detail", "detailed")

models1.Engine.Evidence.Set("Flooding_tunnel", "no")

models1.Engine.Evidence.Set("Explosive_gas", "no")

models1.Engine.Evidence.Set("Buil_ground_impr", "no")

models1.Engine.Evidence.Set("Cutter_disk_Damaged", "no")

models1.Engine.Evidence.Set("Excavation_precautions", "no")

models1.Engine.Evidence.Set("HS_Issues", "no")

models1.Engine.Evidence.Set("Main_bearing_damage", "no")

models1.Engine.Evidence.Set("TBM_Damage", "no")

models1.Engine.Evidence.Set("TBM_stuck", "no")

models1.Engine.Evidence.Set("Tunnel_historic", "no")

state0 = Math.Round(models1.Engine.Belief("Delay_TBM_Tunnel", 0), 4)

state1 = Math.Round(models1.Engine.Belief("Delay_TBM_Tunnel", 1), 4)

state2 = Math.Round(models1.Engine.Belief("Delay_TBM_Tunnel", 2), 4)

state3 = Math.Round(models1.Engine.Belief("Delay_TBM_Tunnel", 3), 4)

state4 = Math.Round(models1.Engine.Belief("Delay_TBM_Tunnel", 4), 4)

MODELTableAdapter. InsertQuery("Strategy1", models1. ModelNodes. Item(8). States(0). Name, state0, models1. ModelNodes. Item(8). States(1). Name, state1, models1. ModelNodes. Item(8). States(2). Name, state2, models1. ModelNodes. Item(8). States(3). Name, state3, models1. ModelNodes. Item(8). States(4). Name, state4)

MODELTableAdapter. Fill (DataSetMODEL. MODEL)

J. BBN Tunnel validation model

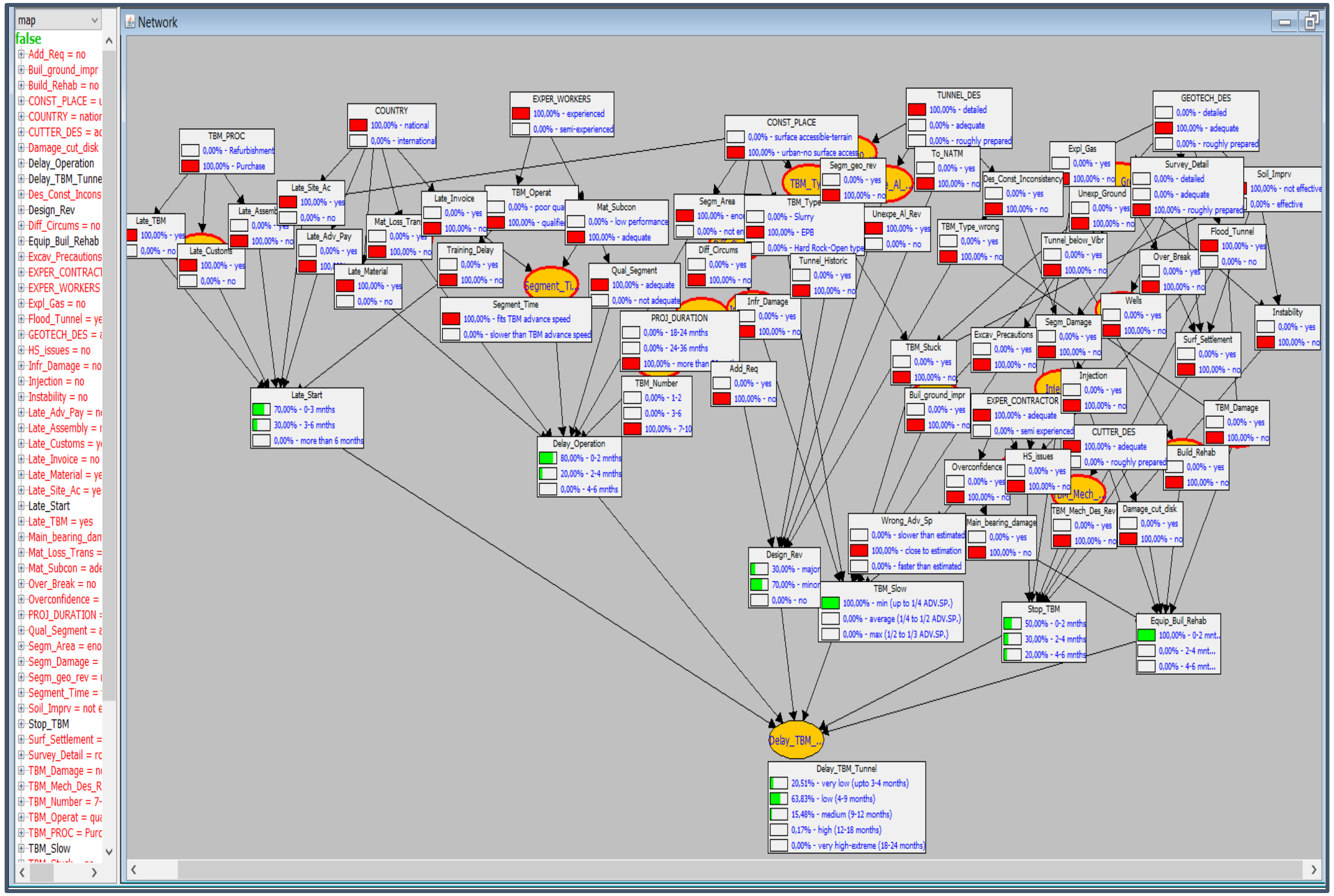

Figure 0.3. BBN Tunnel Model for Predictive Validation Test

CURRICULUM VITAE

PERSONAL INFORMATION

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EDUCATION

Degree	Institution	Year of Graduation
MA. Cert.	Ankara Univ. Faculty of Law	2017
MSc.	METU Civil Engineering	2011
BSc.	Anadolu Univ. Civil Engineering	2008
High School	TED Ankara College Found. High School	2004

WORK EXPERIENCE

Year	Place	Enrollment
2015-Present	Yüksel Proje Uluslararası A.Ş.	Contacts & Cost Estimation Specialist
2014-2014	METU Civil Engineering	Project Research Assistant
2012-2012	Özün Proje	Structural Engineer
2009-2012	METU Civil Engineering	Research & Teaching Assistant

FOREIGN LANGUAGES

Turkish (Native), English (Advanced), German (Limited Proficiency)

PUBLICATIONS

1. Koseoglu, G.C., Canbay, E., 2015, “Assessment and rehabilitation of the damaged historic Cenabı Ahmet Pasha Mosque”, Engineering Failure Analysis, Vol.57, pp.389-398.

2. Balta, S., Koseoglu, G.C., 2014, “Sürdürülebilir Yapılarda SWOT Analizi”, 3. Proje ve Yapım Yönetimi Kongresi, Antalya, Türkiye.

3. Koseoglu, G.C., 2013, “Tarihi Camilerin Yapısal İncelenmesi: Mimar Sinan Camileri”, 4. Tarihi Yapıların Güçlendirilmesi ve Geleceğe Güvenle Devredilmesi Sempozyumu, İstanbul, Türkiye.

4. Koseoglu, G.C., 2011, Investigation of a damaged historical mosque with finite element analysis, MSc. Thesis, METU.

5. Koseoglu, G.C., Canbay, E., 2011, “Investigation of a damaged historical mosque with finite element analysis”, Proceedings of WCCE-ECCE-TCCE Joint Conference 2, Seismic Protection of Cultural Heritage, Antalya, Türkiye.

6. Yaman, H.T., Unal, M., Koseoglu, G.C., 2011, “İnşaat Mühendisliğine Giriş için Etkin bir Yaklaşım: Son 5 yılki ODTU Tecrübesi”, İnşaat Mühendisliği Eğitimi Sempozyumu Bildiriler Kitabı, Muğla, Türkiye.

CERTIFICATES

1. PMP Project Management Certificate, PYD, April 2018, Ankara.

2. Autodesk Revit Architecture, PROTA Computer, December 2017, Ankara.

3. AMP Yaklaşık Maliyet Programı, AMP Akademi, May, 2017, Ankara

4. Public Procurement Law, PROKED Akademi, February 2015, Ankara.

ACHIEVEMENTS

1. Anadolu University, Civil Engineering Department, BSc. 1st Degree Graduation Award

2. Liverpool John Moores University, Department of Civil Engineering, BSc. ERASMUS Program Support Grant.