Automation in Construction 129 (2021) 103819

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Bayesian network based decision support for predicting and mitigating delay risk in TBM tunnel projects

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ARTICLE INFO

Keywords:
Delay risk assessment
Risk management
Decision support
Bayesian belief networks
Tunnels

ABSTRACT

Tunnel projects involve high levels of uncertainty stemming from the vagueness of geological conditions and the complexity of the mechanized tunnel boring process. Delay risk assessment is carried out by project managers to identify critical risk factors leading to time and cost overruns and formulate strategies to meet the project targets under different scenarios. In this study, a Bayesian Belief Network (BBN) based risk assessment method was developed for Tunnel Boring Machine (TBM) tunnel projects to predict delay. Based on the BBN model, a decision-support tool, BBN Tunnel, was developed to assess delay considering the impacts of implementing alternative risk mitigation strategies. The tool developed in collaboration with a company was utilized in a tunnel project to test its usability in practice. The results demonstrated that BBN Tunnel and risk assessment method could be used to model interrelations between risk factors, construct a risk network, predict delay and help decision-makers formulate cost-effective risk mitigation strategies.

1. Introduction

Tunneling projects are large-scale and technically complex infrastructure projects that involve various risks, primarily due to the uncertain nature of underground conditions and tunneling processes [1]. Here, the uncertainty is higher than aboveground constructions regarding both estimated costs and project durations. Project success in tunneling projects is usually measured by schedule performance, where delay leads to cost overruns and disputes between the parties [2–4]. Assessment of delay risk in tunnel projects is important to estimate the impact of uncertainty on cost/duration and formulate necessary risk mitigation strategies to ensure project success.

There are various analysis methods proposed for delay risk assessment in large-scale construction projects. These methods include Monte Carlo simulation, probability-impact matrices and influence diagrams [5,6]. Various authors, such as Eskesen et al. [7] proposed to use probabilistic methods to estimate variability in duration and cost in tunneling projects. Additionally, various authors, such as Al-Humaidi and Hadipriono [8], proposed the fuzzy set theory to assess the risk of delay. Multi-criteria decision-making tools such as Analytic Hierarchy Process (AHP) have also been utilized by authors such as Hossen et al. [9] to assess project delay risk based on probability of occurrence and severity rankings assigned by the experts considering multiple risk factors. Delay risk assessments in these studies usually depend on the prediction of delay without considering how the delay can decrease or get eliminated in the existence of different scenarios on strategy implementation. It is apparent that risk assessment and mitigation shall be iterative steps where the decision-maker makes an initial risk assessment, then considers the implementation of alternative strategies and monitors how the delay risk is expected to change under different scenarios. Based on this idea, this study has two notable differences from the existing studies in the construction risk assessment literature, which are listed below:

1. It presents a comprehensive risk assessment method using the Bayesian Belief Network (BBN) to predict delay and formulate strategies to minimize delay for tunnel projects. A tunnel delay risk taxonomy was developed, and the risk assessment method was used to analyze risks, their interdependencies, contributions to delay systematically and finally, evaluate the effectiveness of alternative risk mitigation strategies.
2. A tool, namely BBN Tunnel was developed to demonstrate how the risk assessment method can be implemented in practice. BBN Tunnel was developed in collaboration with a company, using data on

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https://doi.org/10.1016/j.autcon.2021.103819
Received 20 September 2020; Received in revised form 15 June 2021; Accepted 20 June 2021
Available online 25 June 2021

previous projects and incorporating expert opinions. Then, recommendations were provided for companies that aim to use the risk assessment method and BBN Tunnel.

2. Literature review

2.1. Bayesian belief networks for project risk assessment

BBNs are based on the Bayesian Theorem developed by Thomas Bayes for calculating conditional probability distributions given a set of interacting variables [10]. BBN is defined as a directed acyclic graph representing the conditional dependencies among a group of variables [5]. In the first half of the 1980s, BBNs were introduced as expert systems including the works by Pearl [11] and Spiegelhalter and Knill-Jones [12].Then, from the 1990s, BBNs were frequently being used in computational problem diagnosis [13], agricultural prediction systems [14], software risk management [15] and environmental management [16]. The primary application areas of BBNs in project risk assessment have 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 Conditional Probability Tables (CPTs) among risks and conducting sensitivity analysis to identify major risks, which affect project performance [17,18].

Applications of BBN in construction projects have been reported in the early 2000s. In the literature, only a few researchers attempted to use the Bayesian Belief Network method to investigate the construction risks for delay risk assessment. As one of the pioneering studies, Nasir et al. [5] created a BBN model, named ERIC-S, for assessing schedule risk. The model information was gathered mostly from experts, where triangulation was conducted by project reports and literature surveys. The risk variables were classified into ten categories as environmental, geotechnical, labor, owner, design, area condition, political, contractor, non-labor resources, and material. After testing the model with several cases, outputs of the BBN model were used as inputs to Monte Carlo simulation. The utilization of BBN for large-scale project risk assessment was also demonstrated by Lee et al. [18]. Luu et al. [19] also used BBNs for predicting schedule risk in the Vietnamese construction industry. After developing a BBN with expert sessions, they identified the least and the most crucial factors causing delays. With a detailed literature review on BBNs, Weber et al. [20] examined 200 articles about applying BBNs as a risk analysis method and noted the increase in interest and number of references due to its modeling and analysis capabilities. BBN was chosen over influence diagram, fault trees and cross impact methods, due to its ability to present comprehensive relationships between risk factors and perform analysis by calculating conditional probabilities. The preeminent advantages of BBNs are summarized below [15,16,19].

- BBNs can handle incomplete data sets and work with the available data to achieve accurate results.
- BBNs combine the strength of causal relationships with probabilities and use empirical knowledge and expert data.
- BBN network structure enables understanding relationships between variables.
- Once a model is compiled, resultant probabilities can be achieved quickly through already established CPTs. Thus, the computational effort is comparatively low.
- BBNs learning and network models can be refined to give better results.

2.2. BBN based risk assessment in tunnel construction projects

Tunnel projects involve various risks such as safety and delay risks stemming mainly from geotechnical uncertainties and the complexity of the tunneling process. Yoo et al. [21], Ding and Zhou [22], Kim [23], Zheng and Ma [24], Deng et al. [25], Guo [26], Liu et al. [27], Xia et al. [28] and Koopialipoor et al. [29] used different risk assessment methods from event trees and artificial neural networks to fuzzy methods and evaluate geotechnical risks in tunnel projects. Sousa and Einstein [30] used the BBN method to assess the geological risks and provided a prediction model to analyze the risk of tunnel face collapse, providing decision-makers a choice among open or closed modes for an EPB TBM tunnel project. Cardenas et al. [31] focused on the construction stage of tunnel projects in terms of "deformation/damage of concrete lining" and identified major risks during the construction phase. In Zhang et al. [32]'s work, the aim was to merge BBN and fuzzy logic principles in a Fuzzy Bayesian Network (FBN) and provide an alternative construction failure analysis method for tunnel constructions. Tunnel leakage was identified as the model output. The novelty of this study comes from utilizing Fuzzy Probability Assessments to determine conditional probabilities. The authors implemented this feature by carrying out inference and updating conditional probabilities. Yu et al. [33] also used BBN and Monte Carlo simulation concurrently to estimate the probability of completing the TBM excavation within a specified duration. Their findings showed that although geotechnical conditions dominate the probability of occurrence of risk events, design and management abilities also affect the achievement of the planned project schedules. Chung et al. [34] suggested a BBN-based cost overrun risk assessment method for TBM 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. According to Chung et al. [34], the most widely used risk assessment methods in TBM tunnel projects using risk registers/checklists cannot provide a systematic cause-and-effect analysis and a quantification of delay risk. Therefore, they created a BBN for analyzing risks in shielded TBM excavation operations. Among the many risk assessment methods used for tunnel projects, BBN proved to be one of the most efficient tools to model complex relations between project parameters and risk factors. Foudalgara et al. [35] implemented a multi-criteria decision-making technique and developed a Fuzzy TOPSIS model, aiming to prioritize and select one or more alternatives from a pool of feasible alternatives based on a set of criteria to assess health safety and environmental risks. Naghadehia et al. [36], also developed the "Decision Aids for Tunneling (DAT)" tool, analyzing the geotechnical risk by determining the most efficient excavation-advancement orientations and assessing the variability of time and cost of different construction operations.

3. Research gaps in the literature

Understanding the alternative risk assessment methods for delay prediction of tunnel construction projects is the first step in developing a delay risk model. In this section, relevant studies briefly summarized in the previous section will be discussed to identify the research needs in the risk assessment process of tunnel construction projects.

Although there have been various studies on risk assessment of tunnel projects, most of them focused on geotechnical or safety risks [21,36], ignoring uncertainties stemming from design, tunneling equipment, and management. These studies usually analyze specific failure mechanisms and do not quantify the overall project delay risk. Meanwhile, the research on tunneling risks shows that uncertainties due to design, mechanical factors and management also affect project success significantly [4,7,37]. Konstantis et al. [3] state that risks emerging from geotechnical conditions, design and construction management lead to 80% of project failures, where design errors make up approximately 40%. Consequently, even though geotechnical uncertainties influence project success in tunnel constructions significantly, other risk sources when coupled with geotechnical uncertainties may lead to project failure. It is clear that consideration of a variety of risk sources together with their interrelations would enable a better assessment of the overall risk level of a tunneling project.

Various models have been introduced in the literature for assessing project risks for tunnel constructions [31,32,35,36]. However, there is a research gap when it comes to decision support systems and risk taxonomy. Strategies that can help mitigate delay risk have not been systematically integrated into risk models. Considering implementing risk management strategies can change conditional probabilities and result in a different risk picture for the project, this is a vital shortcoming in previous studies.

Thus, to fulfill the specified research gaps, this research identified a comprehensive list of risk factors affecting project delay and steps of risk identification-analysis-mitigation were integrated for a more realistic assessment of delay. A comprehensive risk assessment method based on BBN and a decision support tool were created for assessing delay risks in tunnel projects. Among the many risk assessment methods used for tunnel projects, BBN has been one of the most efficient methods to model complex relations between project parameters and risk factors. Thus, it has been applied to various tunnel projects [21,36]. The superiority of the method lies in its ability to express a network of interrelated parameters and risks for probabilistic analysis, to conduct a quantitative analysis of dependencies between variables and deal with uncertainties in data. Therefore, BBN was selected as the basis of the risk assessment method and decision support tool in this research.

4. Gaps in practice

This study was carried out in collaboration with a construction company experienced in tunneling projects. Researchers had the chance to investigate how the delay risk in tunnel projects is carried out by monitoring the actual practices of this company. The Company is an international Turkish construction company that is among the largest engineering firms in the country. Having completed many national and international transportation, infrastructure, building and treatment facility projects, the Company is constantly among the top design companies in the ENR list. The Company has been selected as a research partner because of its extensive experience in tunnel projects for over 30 years. The Company has taken part in various risk assessment studies, therefore has a considerable understanding of the procedures implemented in practice and able to provide the expertise and data required to support this research. Risk assessment reports of the four most recent tunnel projects in Turkey, Qatar and Europe were investigated using the company records to understand the risk assessment methods used in tunnel projects and risk registers used for risk identification. Information derived from these reports is in Table 1.

Findings from the case project reports are summarized:

1. In the case study reports, risk factors were listed in separate risk clusters ignoring their interdependencies. Risks were listed separately for cost, time, safety, and quality ignoring relations between these project success indicators. Risk checklists were mainly prepared using subjective ratings assigned by the experts for the probability of occurrence (P) and impact (I) of risks on project success. The interrelations between risk factor and cause-effect relations (risk source and risk event) were neglected in all the risk assessment reports.
2. In some reports, there was no information about risk mitigation strategies, whereas in others, strategies to minimize the “impact” of high priority risk factors were listed. However, how the risk levels would change if these strategies were actually implemented, and the costs of implementing strategies and their effectiveness were totally ignored. In one report, a set of mitigation strategies was defined, and the risk checklist was revised assuming that these strategies would be implemented. However, there was no analysis reported considering different scenarios on implementing strategies and their effects based on a network of interrelated risk factors.

In conclusion, major flaws in the case projects were identified as neglecting interrelations between various risk factors and impacts of strategies (also costs) considering risk dependencies. When the interrelations between risk factors are ignored, subjective risk ratings assigned by the experts cannot reflect the propagation/triggering effects leading to an unrealistic overall risk rating and erroneous risk prioritization. When mitigation measures are not incorporated, how the project risk and cost/time will change under different scenarios (when multiple, some, or none of the strategies are implemented) cannot be monitored by the decision-makers. Thus, it is concluded that a methodology and a decision support tool are needed to incorporate interrelations between the risk factors leading to delay and incorporating strategies to assess their effects on the project. Company professionals also agreed on the necessity of such an approach for a more realistic risk assessment in tunnel projects.

5. Scope and objectives of the study

Based on the gaps identified from the literature and case projects, this paper aims to develop a risk assessment method for TBM tunnel projects that take into account interrelations between risk factors and develop a decision support tool to incorporate strategies into the risk assessment process to provide accurate delay predictions using Bayesian techniques.

6. Development of BBN tunnel: a tunnel delay risk assessment tool

The decision support tool has been created using the delay risk assessment method as illustrated in the flow chart given in Fig. 1 that is composed of three key steps. The first step involves the creation of a tunnel delay risk taxonomy. In the second step, the computational BBN model was developed to predict a delay in TBM tunnel projects by using the taxonomy. Then, sensitivity analysis was carried out to identify the

Table 1
Summary of case projects.

Project	Total length	Risk assessment methods	Mitigation strategies	Outputs
A motorway tunnel in Istanbul	3.4 km	A subjective rating approach with Probability-Impact (P—I) matrices to assess cost overrun and schedule risks, separately. Monte Carlo simulation to calculate delay risk.	Strategies were identified to minimize the “impact” of prioritized risk factors.	Lists of critical risk factors for cost and time overruns. Critical activities for the delay.
A railway tunnel in Istanbul	9.8 km	A subjective rating approach with P—I matrices to assess cost, schedule, safety and quality risks.	Risks were prioritized but no mitigation strategies were identified.	Lists of critical risk factors for cost, time, safety, and quality.
A railway tunnel in Europe	7 km	A quantitative “risk cost” measurement formula that uses the subjective probability of occurrence and cost impact of identified risks. Assessment of acceptability of identified risk factors.	None	Net risk-opportunity cost of the project. List of risk factors considering their acceptability.
A railway tunnel in Qatar	10.5 km	A subjective rating approach with P—I matrices to assess cost, schedule and safety risks.	Strategies were identified to minimize the “impact” of prioritized risk factors.	Lists of critical risk factors for cost, time and safety. Final lists of critical risk factors after “mitigation measures”.

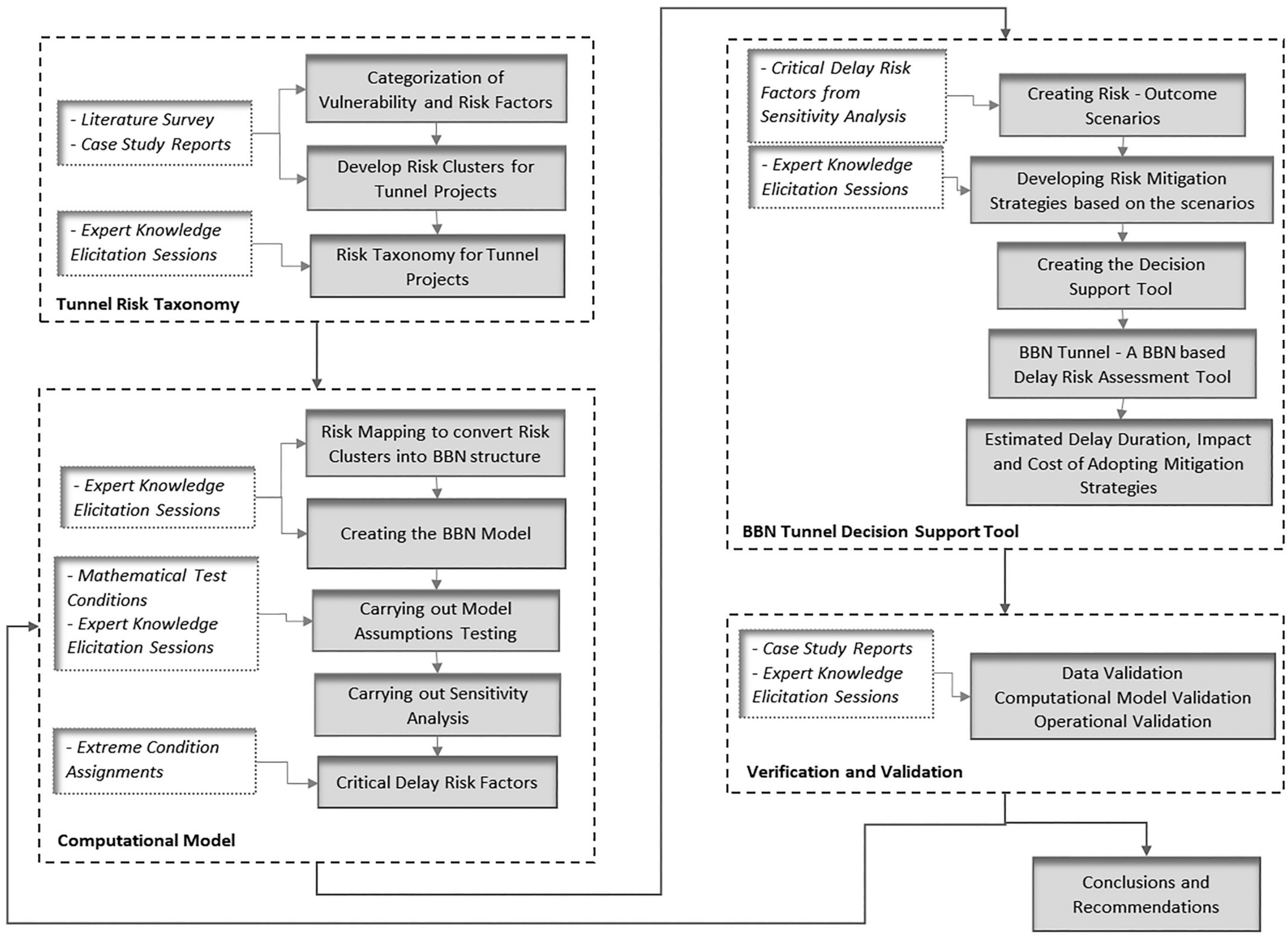

Fig. 1. Methodology.

most significant parameters influencing project outcomes to develop risk mitigation strategies. Finally, in the third step, BBN Tunnel Delay Risk Assessment Tool (namely, BBN Tunnel) was developed, and project delay risk was re-analyzed while considering risk mitigation strategies. The tool calculates the estimated project delay in TBM tunnel projects and proposes alternative risk mitigation strategies to reduce delay.

Expert knowledge elicitation (EKE) methods were utilized in various stages of this research. Interviews, questionnaires, focus groups and concept sorting sessions were carried out to develop BBN Tunnel. The participants of these sessions had a minimum of 10 years of experience

Table 2
Information about experts.

Expert	Profession	Position	Professional Experience	Field of Experience About Tunneling		Participation in the study
A	Civil Engineer	Project Manager	10 years	Design and consultancy	Project control engineer in railway and infrastructure tunnel projects	Tunnel Delay Risk Taxonomy, Risk Mapping
B	Civil Engineer	Project Manager	10 years	Design and consultancy	Project control engineer, Postgraduate degree in tunneling field	Tunnel Delay Risk Taxonomy, Risk Mapping
C	Civil Engineer	Senior Manager	20 years	Design and consultancy	Project control, Project management of railway and infrastructure tunnel projects	Computational Model
D	Mechanical Engineer	Senior Manager	20 years	Design and consultancy	Project control, Project management of railway and infrastructure tunnel projects	Computational Model
E	Civil Engineer	Division Head	15 years	Design and consultancy	Project control engineer in railway tunnel projects	Computational Model
F	Civil Engineer	Division Head	15 years	Construction (on-site experience)	TBM Tunnel field engineer, Project management of railway tunnel projects	Computational Model
G	Electrical Engineer	Division Head	20 years	Construction (TBM operations)	TBM tunnel field engineer, Highly experienced in TBM operations, refurbishment	Assumptions Testing, Sensitivity Analysis and Validation
H	Civil Engineer	Project Manager	10 years	Construction (on-site experience)	Project control, Field engineer in metro tunnel projects	Case project modeling and Real case testing
I	Civil Engineer	Project Manager	15 years	Design and consultancy	Project control engineer in railway and infrastructure tunnel projects	Case project modeling and Real case testing

in tunneling projects. These nine experts engaged in data validation, tunnel delay risk taxonomy, quantitative model development, assumptions testing, strategy assessment and real case testing stages of the research are depicted in Table 2.

6.1. Tunnel delay risk taxonomy

The first step of the research was creating of the delay risk taxonomy for tunnel projects. According to Nickerson et al. [38], taxonomy is "a set of dimensions each consisting of a set of characteristics that sufficiently describes the objects in a specific domain of interest". The process in this study comprised two successive phases. In the first phase, namely categorization, risk factors found in the literature were listed and risk and vulnerability factors were identified from the real project risk assessment reports. To conclude the categorization phase, which is the second phase; undirected graphs were used to represent relations between the risk factors [39]. Risk clusters provide means to develop risk categories. For developing the risk clusters, the literature survey was the first method used. The risk factors that were identified in the literature provided an initial list of factors for further research. Actual cases from the company records were investigated to identify risk and vulnerability events that occur in tunnel projects. The risk categories, risk sources and factors were finalized by considering the findings from real risk assessment reports. Literature findings were referred to identify vulnerability factors and risk events for each risk category. Network diagrams of vulnerability factors, risk events and resultant risk factors were determined, as well as the expected deviations from project outcomes. Fig. 2. depicts the risk cluster for an advance rate of TBM. The aim was to visualize the risk categorization structure, to highlight the common triggers, risk events and their consequences. Risk clusters form the basis for capturing complex interactions between risks ranging across different domains in a tunnel project, which were used to obtain expert opinions in the forthcoming steps of the study.

Risk categorization lists and risk clusters were reviewed and evaluated with a questionnaire distributed to the experts. This process aimed to explain the draft model to the experts and revise or verify the risk factors and categories according to their comments. Two experts from 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 the light of these, the pre-assessed risk factors and risk categories were validated and factors with minor influence on construction delay were eliminated. After the results of the questionnaires were attained from the experts, the confidence levels of the experts were determined, and average ratings were calculated using their confidence levels of 0.55 and 0.45 according to their experience in the field. The weighted averages of risk factors for "TBM Advance Rate" achieved by aggregation of questionnaire results are given in Table 3.

Information gathered from expert judgements may contain a certain level of uncertainties. Therefore, elicitation from multiple experts can lead to solutions that are more accurate. If multiple experts are included in the process, the primary aim is to propose a single distribution considering the alternative views of various experts. The aim can either be achieved by reaching a consensus among the experts through group discussions or by obtaining individual responses from the experts and then aggregating them. When the second option, aggregation is used, a resultant probability distribution has to be accomplished by combining different views elicited from experts considering their confidence levels. In this study, the weighted average ratings are obtained through the mathematical aggregation of separate expert judgements on each remaining risk factor and risk event, as given in Table 3.

Over this data given in Table 3, discussions were conducted with the experts in a separate session. The experts re-evaluated the risk ratings, and it was expected from the experts to reach a consensus over the undirected graphs distributed to them and the results of the questionnaire. The risk events, risk factors, and the risk consequences were discussed, and a final risk cluster was obtained at the end of this session. In the light of these, the authors analyzed the final risk clusters and tabulated the resultant data, as given in Table 4.

6.2. Computational model

Successive phases were carried out to develop the BBN based delay risk assessment model. The first phase was "risk mapping" in which the risk clusters were combined; interrelations were determined and converted into a BBN structure. To transform the risk clusters into a BBN structure, the graphical mapping method developed by Khakzad et al. [43] was used. The connections were established through separate concept sorting sessions with the experts, using the MSBNx [44] software. After the causal mapping stage was concluded, the authors modeled the preliminary BBNs. During this process, differences between the experts were identified. It was seen that because of the complexity of relations, the computational model became highly complex, and the visualization capabilities of the software became highly inefficient. Therefore, in order to decrease the dimensions of interdependency relations, the "divorcing the parents" method [45] was implemented

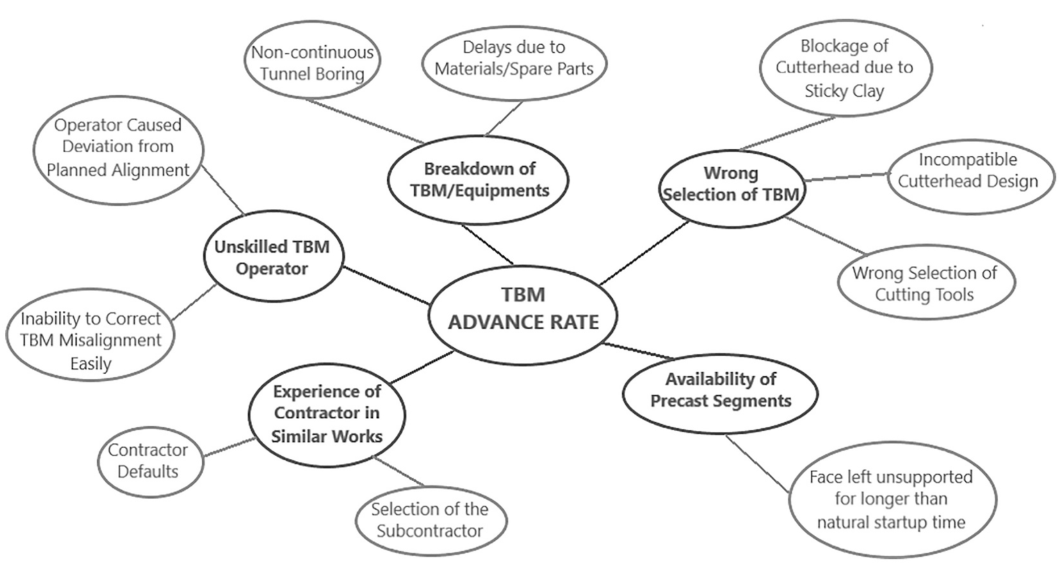

Fig. 2. Risk cluster "TBM Advance Rate".

Table 3
Taxonomy questionnaire for tunnel delay risk.

TBM advance rate	Importance rating by expert 1	Importance rating by expert 2	Weighted averages considering confidence levels
Unexpected Problems in TBM Procurement/Late Delivery of TBM	7	1	4
TBM Procurement Method (ownership/ renting/refurbishment)	8	6	7
Delay in Mantling of TBM	7	1	4
Number of TBM Machines	1	2	1
Delays in Getting Permits to Start TBM Works	10	3	7
Wrong Assumption of TBM Advance Rates	5	2	4
Loss of Power to TBM	9	2	6
Breakdown/Damage of TBM	3	2	3
Wear of the Cutter Tools	4	4	4
Availability of Precast Concrete Segments When Needed	8	6	7
Slurry Pipeline Failure	–	–	–
Unskilled TBM Operator	5	4	5
Operator Caused Deviation from Planned Tunnel Alignment	6	4	5
Non–continuous Boring through Fault Zones	6	3	5
Collapse or Excessive Deformation of Linings Approaching the Tunnel	4	3	4
Finding Archaeological Artefacts	1	1	1
Alignment Conflicts with Existing Underground Structure/Cavity	2	3	2
Utility Relocations that is not Foreseen in Data Received from Authorities	3	6	4
Damage to Existing Buildings	2	5	3
Logistical Difficulties and Volume of Muck Disposal	–	–	–

Table 4
Taxonomy for tunnel projects delay risk.

Risk events	Risk factors	Reference	Risk consequences
Detail of geotechnical design	Explosive Gas Leakage into Tunnel, Unexpected Ground Conditions	[31,40]	Damage to Equipment and Buildings, H&S Issues, TBM Stoppage, Decrease in TBM Advance Rate
	Detail of Ground Surveys, Effectiveness of Soil Improvement before Excavation	Case Study Reports	
Detail of tunnel design	Unexpected Alignment Revisions, Segments Geometric Design Not Meeting Project Requirements, Change in Construction Methods (from TBM to NATM)	Case Study Reports	Design Review, Segments Damage, Equipment Damage
	Inconsistency Between Design Assumptions & Construction Method	[41,42]	
Detail of cutter head design	Mechanical Design not Meeting Project Requirements	Case Study Reports	Damage to Equipment, TBM Stoppage
	Damage to Cutter head	[41,42]	
Contractor's experience	Overconfidence in Construction Methods	Case Study Reports	Decrease in TBM Advance Rate, Damage to Surrounding Structures
	Health and Safety Issues	[41]	
Place of construction	Delays in Site Access, Different Circumstances Compared to Data from Authorities	[40]	Delays in Operations
Project duration	Number of TBM Machines	Case Study Reports	Delays in Operations, Design Review
	Employer's Additional Requirements	[40]	
Experience of workers	Experience of TBM Operator, Performance of Segment production Sub-Contractor	Case Study Reports	Late Start, Delays in Operations
Country of construction	Delays in Site Access, Delays in Material Supply, Delays in Progress Payments	[40]	Late Start, Delays in Operations
	Material Loss during Transportation, Delays in Advance Payment	Case Study Reports	
TBM procurement method	Delays in TBM Procurement, Delays in Customs Clearance, Delays in TBM Assembly	Case Study Reports	Late Start

before experts' re-evaluation. In the second risk mapping session, the created final BBN models on MSBNx [44] were shared with the experts. Their preliminary models were introduced, and the differences were explained by the authors. In this regard, each relationship was explained thoroughly, and experts were encouraged to discuss these causalities for reaching the project delay. This session was 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 best solution for creating the risk of breakdown structure of the BBN model. As a result of this procedure, the conceptual BBN model was completed. The final risk assessment model comprises 64 nodes and 99 edges. In order to construct the computational BBN model (Fig. 3), four additional EKE sessions were used to determine the Conditional Probability Table (CPT) states, understand the causal relationship between these risk events and their interdependency rates.

Each session was conducted using the BBN model in MSBNx [44] software. After each session, experts had a re-evaluation period for reviewing their answers and revising if necessary. This process was carried out because, each session provided input/part of the following session. In the first session, the states of the risk factors were determined. The expert reviewed the BBN model on MSBNx [44]. The 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 were entered into a data registry form developed by the author. After the constructed states were entered into the MSBNx[44]'s BBN model, three separate sessions were carried out with three different experts. In this regard, each relationship was explained in detail, and experts were encouraged to discuss these causalities for reaching the project delay. Each expert was 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 [44] software. This process started with the root nodes of the model and was preceded by intermediate and leaf nodes. The software possessed visual limitations for nodes with over three parents. Therefore, each session took almost five hours and a break was required during the sessions. After each session, experts had a re-evaluation period for reviewing their answers and doing revisions, if necessary. At the end of these separate sessions, the BBN models quantified by the expert interviews were reviewed by the author. The conflicting node assignments were elected from the model. These

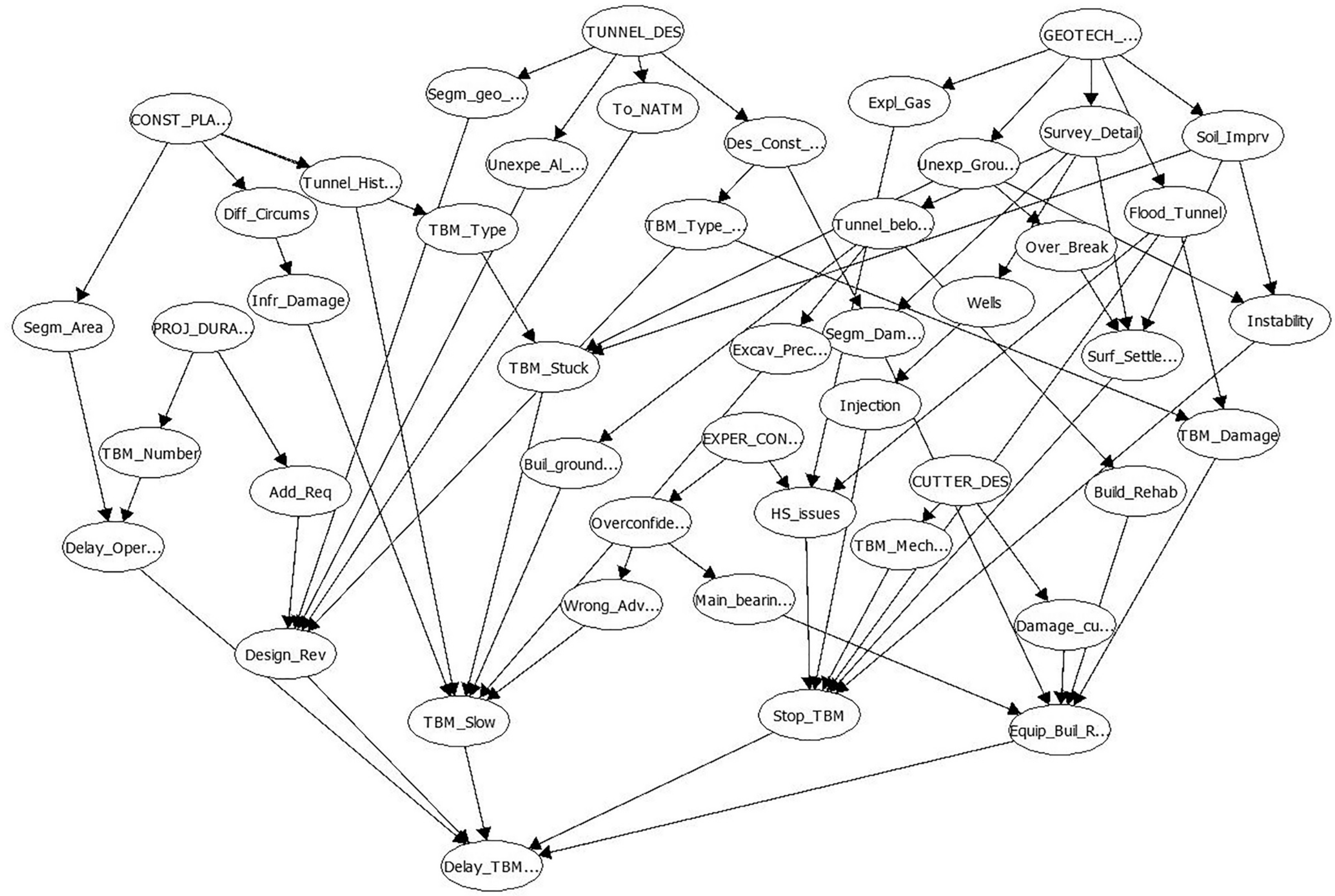

Fig. 3. Computational BBN Model.

assignments were then shared with the experts in a group meeting. In presence of the author, the 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.

In the sample CPT table, the parent nodes of the "surface settlement" and the states of the node determined as yes/no can be seen. From Table 5, it can be evaluated that surface settlement depends on the detail of the geotechnical survey, the effectiveness of soil improvements and presence over break. As a result of the described procedure, in light of expert knowledge elicitations, the probabilities of occurrence of each of these states are determined. To elaborate, for example, according to Table 5, if the geotechnical survey is sufficiently detailed and implementation of soil improvement methods is effective and there is no over break; the probability of occurrence of surface settlements in the TBM tunnel is only 15%.

The BBN-based risk assessment model was then subjected to a series of mathematical assumption tests. Due to its efficiency in identifying and revising the model probabilities according to the desired outputs, SAMIAM [46] software was used to conduct these model assumption tests. After modeling the BBN into the SAMIAM [46] software, test conditions were developed by the authors and results were discussed with experts. The final test conditions, relevant assumption control factors (ACF) and their model outputs are summarized in Table 6.

At the end of this stage, the contents of the model were completed with the experts and the chosen model was found adequate to represent the Company's tunneling expertise on conducted tunnel projects. The computational model corresponds to a BBN-based delay risk assessment model, which uses the advantages of Bayesian networks, and it provides a network structure of tunnel risks considering their correlations. The interdependencies between risk factors have been determined considering 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. In addition, 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 last phase of this stage contained sensitivity analysis to identify the critical risk factors for delay risk assessment. The sensitivity analysis can be broadly described as the identification of parameters that affect a model and problem output [47]. In BBNs, this analysis helps to

Table 5
CPT table of surface settlement node.

Survey detail	Parent nodes		Child node	
	Soil improvements	Over break	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%

Table 6
Assumption control factors (ACF) for test conditions.

Assumption control factors (ACF)	Model requirements/Outputs
ACF 1: For smaller projects (durations 18–24 months), if only no other risk events occur,	"Very high delay" is not likely to be encountered.
ACF 2: TBM machine can be trapped in the soft ground only if,	TBM machine is hard rock open type.
ACF 3: If ACF 2 occurs,	Extreme design revisions will be necessary; delay in the project is estimated to be at least 6–9 months.
ACF 4: If the TBM machine stops about 4–6 months, If the tunnel project starts late over 6 months, If operational delays during the TBM tunneling sequence reach 4–6 months	Project delay is expected to be over 4 months, it becomes impossible that the project is finished with very low delay; project delay cannot be less than 4 months.
ACF 5: Although it is most unlikely that the geometry of these segments does not meet the tunnel geometry requirements, in the occurrence of such a case	Comprehensive design revisions would be certainly required.
ACF 6: In TBM tunnel projects, the tunneling proceeds in a linear operation. The length of the tunnel and the number of TBMs determine the duration of the project.	This control factor limits the number of TBMs according to the duration of the project.

understand the relationships between network parameters, their global behavior in the network, identifying variables that do not affect the output and thus are not required for further analysis and variables that could be considered being changed to reach a satisfactory global probability distribution [48,49].

Sensitivity analysis was based on the extreme condition assignments. For 63 root and intermediate nodes in the BBN model, 2×63 states were defined and their effects on project delay were 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 are given in Fig. 4. This procedure showed that the factors in project duration were most sensitive to;

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

When intermediate nodes were evaluated, TBM mechanical design reviews and tunnel flooding were found as the most influential factors that tunnel project delays were most sensitive to. Excessive water inflow could lead to extensive damages to constructions as well as machines leading to high recovery periods to proceed to the tunnel. For mechanical revisions, accurate geological information is the key factor for tunnel and mechanical design. If unexpected soil conditions are faced during excavation that was not considered during the selection of the TBM machine being used, then critical conditions like squeezing would result, which could also necessitate a change in the cutter head. Such a revision would require stoppage in the boring process. The computational model shows that cutter head design detail is more important than detail in geotechnical design.

6.3. BBN tunnel: decision support tool

To automate the calculations carried out in the model and to increase the usability of the developed method especially for those users that are not experienced in probabilistic methods such as BBNs, a tool was developed. The BBN computational model and the critical risk factors determined in the previous step, forms the basis of the decision support tool (BBN Tunnel).

BBN Tunnel was developed to predict the delay in tunnel projects considering potential risk mitigation strategies (scenarios) that can decrease delay. According to the risk management framework defined by Cohen and Kunreuther [50], scenario creation makes up a useful step for developing risk management strategies. As specified by Miller and Waller [51], scenarios provide a top-management perspective in terms

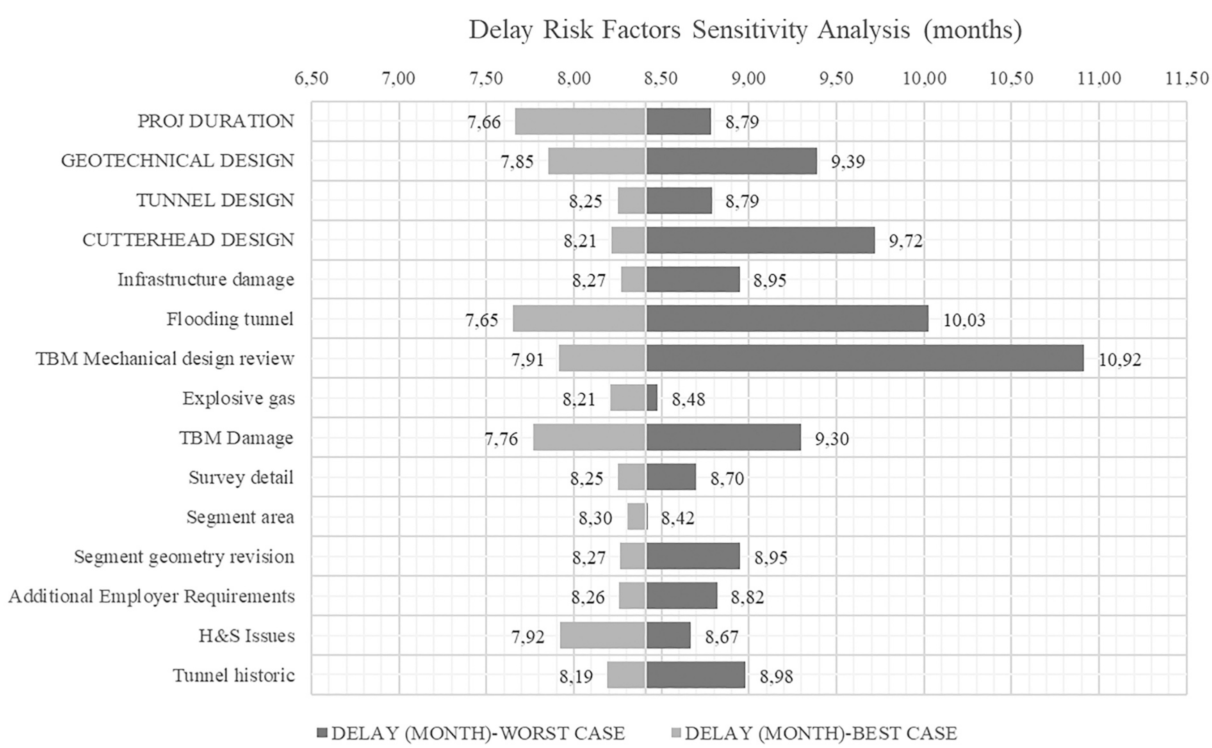

Fig. 4. Sensitivity analysis results.

of problem evaluation and provide 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 [52,53]. This approach allows analyzing different alternative futures to understand which factors contribute more to the outcomes. Thus, based on the scenario creation principles of Ackermann et al. [53], intermediate and root nodes of the sensitive risk parameters, and determined from sensitivity analysis, were grouped by the authors to resemble scenarios that would cause delays in tunnel projects. This resulted in six scenario groups. Then these scenarios were considered to determine risk mitigation strategies. If the delay risk is desired to be decreased, it is suggested that these risk factors in each scenario group would 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 gives the outcome of implementing these risk mitigation strategies. Strategies were reviewed by the company experts and implementation costs of the strategies were estimated. Six strategies formulated are listed below:

- Strategy 1- Improving the geotechnical design level/maturity: Measures were taken such as increasing the detail of geotechnical design by additional boring logs along the tunnel alignment and preventing flooding of the tunnel by utilizing dewatering systems.
- Strategy 2- Increasing health and safety precautions: Additional precautions were taken to improve health and safety levels on site. These precautions included installing instruments for measuring the amount of gas leakage in the tunnel additional horizontal drilling equipment on the TBM to determine any critical changes in the soil characteristics and obtaining insurances for major accidents during construction.
- Strategy 3- Minimizing the design revisions: Measures were taken to decrease the risk of design revisions during construction. These precautions included preventing any changes required in segment geometry or determining the tunnel parameters accurately in advance by obtaining special consultancy services and providing an adequate amount of information to the TBM manufacturer to determine the type of TBM correctly.
- Strategy 4- Minimizing variation in TBM advance rates: Measures taken such as obtaining more ground data to minimize the risk of TBM slowdown due to major infrastructure damages or TBM being stuck during advancement.
- Strategy 5- A partial control mechanism: Measures were taken to improve each design detail involved in the tunneling process, such as cutter head design by customization in the TBM manufacturing process.
- Strategy 6- Full control/mitigation: All possible strategies were made to reduce the probability of occurrence and/or impact of significant risk factors such as adequate segment storage area, supply of an additional TBM, improved coordination between design-construction operations by IT solutions, increasing geotechnical survey detail by additional horizontal drilling equipment, and enhancing tunnel safety conditions by additional water removal measures such as pumping, including gas detection systems.

BBN Tunnel was linked with the computational BBN model incorporating possible strategies to mitigate the delay. In the computational BBN model, the dependency assignments were carried out in the model diagram by entering the CPTs of each node. This feature was also used to evaluate the extreme condition testing by entering evidences to the desired node. It was used in sensitivity analysis and many of the validation tests that were detailed in the previous sections. The BBN Tool on the other hand has been developed via the Microsoft Visual Studio [56] software. The tool provides a decision support mechanism for decision makers, by inputting project properties to the tool they can get risk assessment results and mitigation strategy options as outputs.

As depicted in Fig. 5, the data processing was carried out with the interaction of two systems; the user interacting system through the "problem definition" agent, and the interface that runs the BBN model and delivers its results to the user via the "decision support" agent.

The left side of the user interface screen, named as the "problem definition" window, provides the data input section. Here, a set of 20 input parameters are listed with dropdown boxes, determined in light of the sensitivity analysis. The user/decision maker defines the properties of the tunnel project by selecting the states from the set of dropdown boxes. When a user enters the information about the project, BBN Tunnel carries out the risk assessment process in the BBN model by assigning selections made in the "problem definition" agent and predicts the delay duration. 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. In addition, an expected delay duration is provided to the decision makers in months.

The primary aim of this research has been identified as providing a decision support mechanism for tunnel practitioners. In order to provide the decision-making objective, during research development it was seen that the results of risk assessment alone are not sufficient and a comparative risk mitigation system has to be developed. Therefore, the strategies formulated are also 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. Here, the nodes identified in these six strategies are assigned to their best states. For each of these strategies, the result of "TBM tunnel delay" is retrieved and loaded in the "decision support" window. In addition, the percentage cost of adopting each of these strategies with respect to total project budgets is also given. As a result, the "decision support" agent provided the delay duration for the modeled tunnel project and comparative data for different risk mitigation strategies to reduce and minimize the time overrun. These comparison data comprise both expected delay durations and the cost of implementing identified strategies.

As a result of the procedure described, the developed tool 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 carrying out comparative calculation of the results and cost impacts of these strategies. Instead of the intuition-based processes utilized in current practices of case projects, the computerized risk assessment and mitigation method enabled the prediction of delay in a quantitative system. It combines historical and probabilistic 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 with the model's ability to update considering the newly acquired information.

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 precisely 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 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 got from the sensitivity analysis of the generated computer model and strategy assessment concepts. Post-project information has 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, the cost impacts of each strategy have been included. When these aspects are combined, the developed decision support tool enables practitioners to calculate the

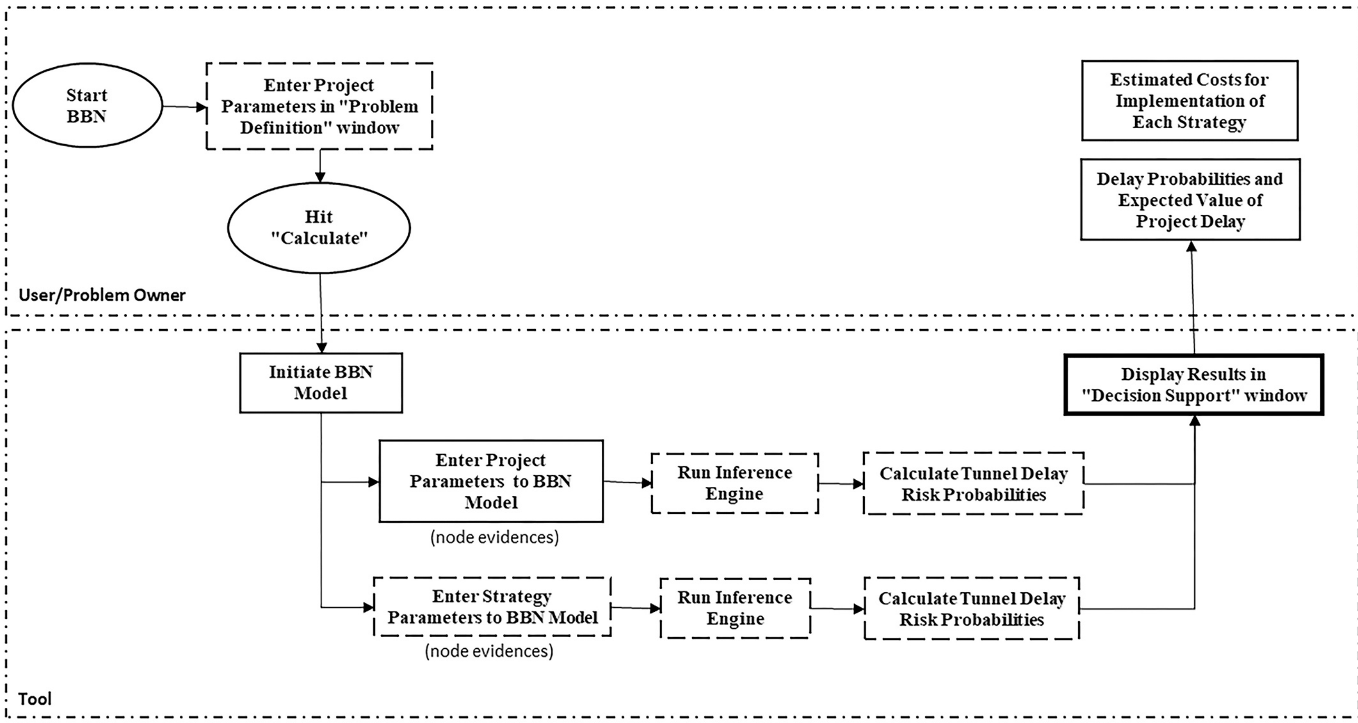

Fig. 5. Process flow diagram of the BBN tunnel.

expected delay durations in their projects, judge between different strategies and identify the most feasible option to reduce delays in tunnel projects.

7. Results

In this section, the results and performance of the BBN Tunnel are demonstrated. Two different stages were designed for this purpose: the validation phase and the real case testing phase. In the first phase, ten verification and validation tests were analyzed to determine if there is enough information to mimic the actual system behavior and the differences between the output produced by the method and the actual projects. Then, an additional real case-testing phase is carried out, with an actual project different from those in the first phase, to demonstrate

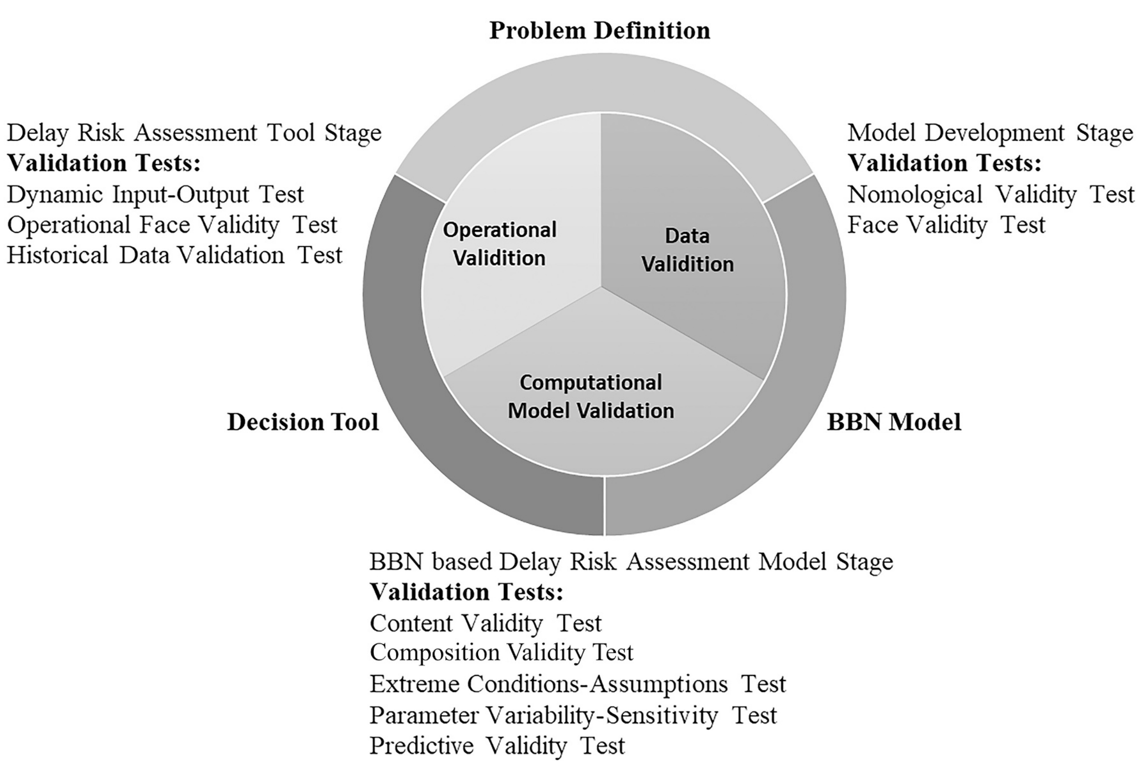

Fig. 6. Validation methodology.

the developed methodology and the decision support tool altogether, and to determine if the results provide valuable information.

7.1. Verification and validation

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 a series of procedures in verification and validation tests to ensure their model can represent the real cases with sufficient accuracy. According to Pitchforth and Mengersen [54], 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". It comprises evaluating a model's level of accuracy in representing the actual system behavior until sufficient confidence is reached. Meanwhile, model verification is the process of ensuring that the developed system works correctly [55]. In this study, research by Sargent [47], Pitchforth and Mengersen [54], and Barlas [57] were taken as the basis for developing the validation methodology. The validation methodology given in Fig. 6 was developed in order to meet the specific needs and objectives of the research. The employed methodology intends to test the verification and validity of BBN-based research and establish confidence in model validity using the information on the domain and specific tests.

The tests given in Table 7 were conducted to ensure the model and tool are constructed, consist of adequate information and mimic the real system behavior with sufficient accuracy. The nomological validity, face validity, content validity, composition validity, parameter variability, predictive validity, operational face validity and historic data validation tests examine the validity of the data and BBN model i.e., if there is sufficient information to create the model and if the methodology and the BBN Tunnel tool generate results with sufficient accuracy when compared to real system behavior. Additionally, in extreme conditions-assumptions test and dynamic input-output tests the verification of the model is evaluated in terms of meeting the assumptions on the subject and ensuring the data are processed correctly. Due to the successive steps carried out to develop the BBN Tunnel tool which was based on the computational model, specific validation and verification steps were incorporated in the development process of this study. The Content Validity Test, Extreme Conditions-Assumptions Verification Test, and Parameter Variability-Sensitivity Test have been used through the development process of the model and decision support tool.

Table 7
Validation tests.

Validation test	Purpose	Procedure
Nomological Validity Test	If the model forms part of a wider domain	Establishing a group of data in the model that fits in an appropriate context in the literature, further data verification is carried out in the first Expert Knowledge Elicitation (EKE) session
Face Validity Test	If model structure & relations represented adequately	Questions are directed at EKE session
Content Validity Test	If the model contains all risk factors, relations	EKE session to determine if the model is in detail
Composition Validity Test	If the model comprises sections/sub-networks similar related subjects	EKE session to determine if the model has sub-networks
Extreme Conditions-Assumptions Test	If evidences provide accurate results	Assumption testing procedure EKE session
Parameter Variability-Sensitivity Test	If key parameters correspond to real system behavior	Sensitivity analysis discussion EKE session
Predictive Validity Test	If the model complies with real system observations	Case project data entered in EKE session
Dynamic Input-Output Test	If the model and tool correctly affiliated	Dynamic tests conducted by author
Operational Face Validity Test	If tool structure and outputs satisfy the intended purpose	Questions are asked in EKE session
Historical Data Validation Test	When historical data entered if the tool provides adequate results and decision support capabilities	Case project data entered by the experts in EKE session

7.1.1. Nomological validity test

At the end of the first EKE session, the experts were 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 nomological "adjacent risk factors" that would be shared among other tunnel projects as given in Table 8.

7.1.2. Face validity test

The face validity test was carried out to determine if the created BBN model structure satisfactorily reflects the real system. This test was established from the viewpoint of the experts by asking questions about the model. After the finalized BBN model structure was constructed, based on the work by Pitchforth and Mengersen [54], the following questions were addressed to the experts;

1. Does the model network structure adequately represent TBM Tunnel Projects?

   "Yes. The model structure is able to represent TBM projects and the created network and nodes distinct for TBM projects specifies them in sufficient detail."
2. Are the parent-child relationships, risk events and consequences adequately constructed for the intended research purpose?

Table 8
Results of nomological and composition validity tests.

Nomological validity test	Composition validity test, sub-networks	
Adjacent Risk Factor	Risk Event	Risk Factor
Explosive Gas Leakage into Tunnel	Detail of Geotechnical Design	Explosive Gas Leakage into Tunnel
Unexpected Ground Conditions		Unexpected Ground Conditions
Detail of Ground Surveys		Detail of Ground Surveys
Effectiveness of Soil Improvement Before Excavation		The Effectiveness of Soil Improvement Before Excavation
Unexpected Alignment Revisions	Contractor's Experience	Overconfidence in Construction Methods
Inconsistency Between Design Assumptions & Construction Method		Health and Safety Issues
Overconfidence in Construction Methods	Experience of Workers	Experience of TBM Operator
Health and Safety Issues		Performance of Segment production Sub-Contractor
Late Site Access	Country of Construction	Delays in Site Access
Different Circumstances Compared to Data from Authorities		Delays in Advance Payment
Employer's Additional Requirements		Delays in Material Supply
Delays in Site Access		Material Loss During Transportation
Delays in Advance Payment		Delays in Progress Payments
Delays in Material Supply		
Material Loss during Transportation		
Delays in Progress Payments		
Delays in Customs Clearance		
Tunneling Below Historic Artefacts		

"Yes, the relations and their construction from root to end and finally to project delay seem accurate."

3. Is the detail level of the network sufficient to include all necessary relationships for delay risk factors for TBM Tunnel projects?

   "Yes. The nodes and the BBN model are in adequate detail. Thus, further detailing is not necessary as it would increase the computational effort and would have a minor effect on the model."

4. Are the sub-networks in the structure provide a detailed assessment base for accomplishing delay prediction?

   "When the sub-networks are examined, it is possible to say that they are in ample detail. The sub-groups have enough nodes, drawing apart from root nodes. As mentioned before, further detailing of these groups is not necessary as it would increase the computational effort and would have a minor effect on the model."

At this stage, the experts reviewed the network structure, and after 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 were found adequate and the levels of parent-child trees were constructed in sufficient detail.

7.1.3. Content validity test

In line with the methodology presented by Pitchforth and Mengersen [54]; two experts were asked to assess the content validity of the BBN model in terms of the number and range of states, CPT tables that comprise 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 were reviewed and modified by the experts if seen necessary. For instance, the project duration states and the final tunnel delay states were modified, irrelevant states were eliminated and duration ranges between specific nodes were agreed on. Final CPT tables and relations were found adequately detailed to represent the intended problem.

7.1.4. Composition validity test

To assess the composition validity test, just as in the Content Validity Test, the experts were requested to evaluate the model structure. The experts were asked to determine if there are any network groups that can be valuable for other problems, such as NATM type tunnel projects. According to the evaluations of the experts, the sub-networks that can function in different construction projects were determined based on the risk events given in the BBN model. To summarize, the sub-groups in Table 8 were found valuable to be used in other problems to determine the delay risk probabilities.

7.1.5. Extreme conditions-assumptions verification test

The extreme conditions test was aimed to determine the numerical consistency of the CPT assignments, the model's logical behavior in the 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. To do that, the ACFs were discussed with an expert. The outputs were discussed considering real system behavior and additional remarks were requested from experts. In the light of this, ACF 3 given in Table 6 was added to the assumption conditions of the model by the expert and a modification in the CPTs was made in the BBN model. After this modification was done, the previously carried out tests were re-run to assess if the created formulations were still satisfied. The final BBN model gave reasonable outputs compared to the real system behavior.

7.1.6. Parameter variability-sensitivity test

Based on the works of Sargent [47] and Barlas [57], each of the model parameters was tested to identify the ones that the model is highly sensitive to. The authors carried out a comprehensive analysis to test each node to its best-worst state. After these outputs were graphically visualized, the results were discussed with the experts. At this stage of the study, the model was "validated" 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.

7.1.7. Predictive validity test

During this predictive validation session, data from three wastewater tunnel projects were entered into the BBN model using SAMIAM [46] software. Projects were selected as the expert encountered and solved critical tunnel construction problems. The expert consulted in this test has 20 years of expertise in the TBM tunnel works and could interfere with high-risk situations in these projects. The evidences for BBN nodes and the results of the predictive validity session are provided in Fig. 7. The evidences were entered into leaf and intermediate nodes and the resultant probability values of the root nodes as well as the delay duration estimation in the final node were evaluated with the expert. As the TBM expert set evidences to each node in the model, it was ensured that the BBN model was valid under the Predictive Validity Session.

7.1.8. Dynamic input-output verification test

After the computational tool was developed, a series of dynamic input-output tests were carried out by the researcher to ensure the tool and model are integrated and the tool retrieves data from the model correctly. To observe the output behavior of the tool, each problem parameter was assigned with its every possible state through the BBN risk assessment model as well as the risk assessment tool. 45 evidence assignments for the twenty nodes were entered in the BBN model. The results were compared with the output given in BBN Tunnel. Similarly, to examine the results of strategic risk assessment, a total of $76 \times 20 = 1520$ strategy assignments were introduced in the BBN model. Each of these outputs was compared with the BBN Tunnel output results. At the end of this series of assignments, it was seen that the BBN Tunnel tool can 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 [44] model.

7.1.9. Operational face validity test

Operational face validity test was similar to the face validity test that was conducted in the data validation stage. However, the face validity test was directed towards assessing the behavior of the computational tool rather than the BBN model. The operational face validity test was conducted by asking the following set of questions to experts,

1. Does the decision support tool provide valuable information for the assessment of delay risk in TBM tunnel projects?

   "Yes, it is valuable to obtain an estimate of delay duration for these projects in order to address any important issues faced that would cause critical delays, which may also cause other contractual penalties."

2. Are the root nodes and sensitivity parameters adequate for data collection stages in the assessment process?

   "Yes, it is reasonable to enter data into the given root nodes. The top five factors in the graph (Fig. 4) are the most critical ones that lead to delays in TBM tunnel projects. For example, mechanical design revisions occur due to the provision of inaccurate data during the TBM manufacturing process. In case of this, critical conditions like squeezing would occur which could also necessitate changes in the cutter head. Such a revision would require stoppage in the boring process and cause considerable delays in the project."

3. Is the user interface understandable for the decision makers in the industry?

   "The tool is understandable, but in terms of the results provided by the tool beside the probability distribution of delay durations a single estimate of delay should be given. This would be much clearer, and

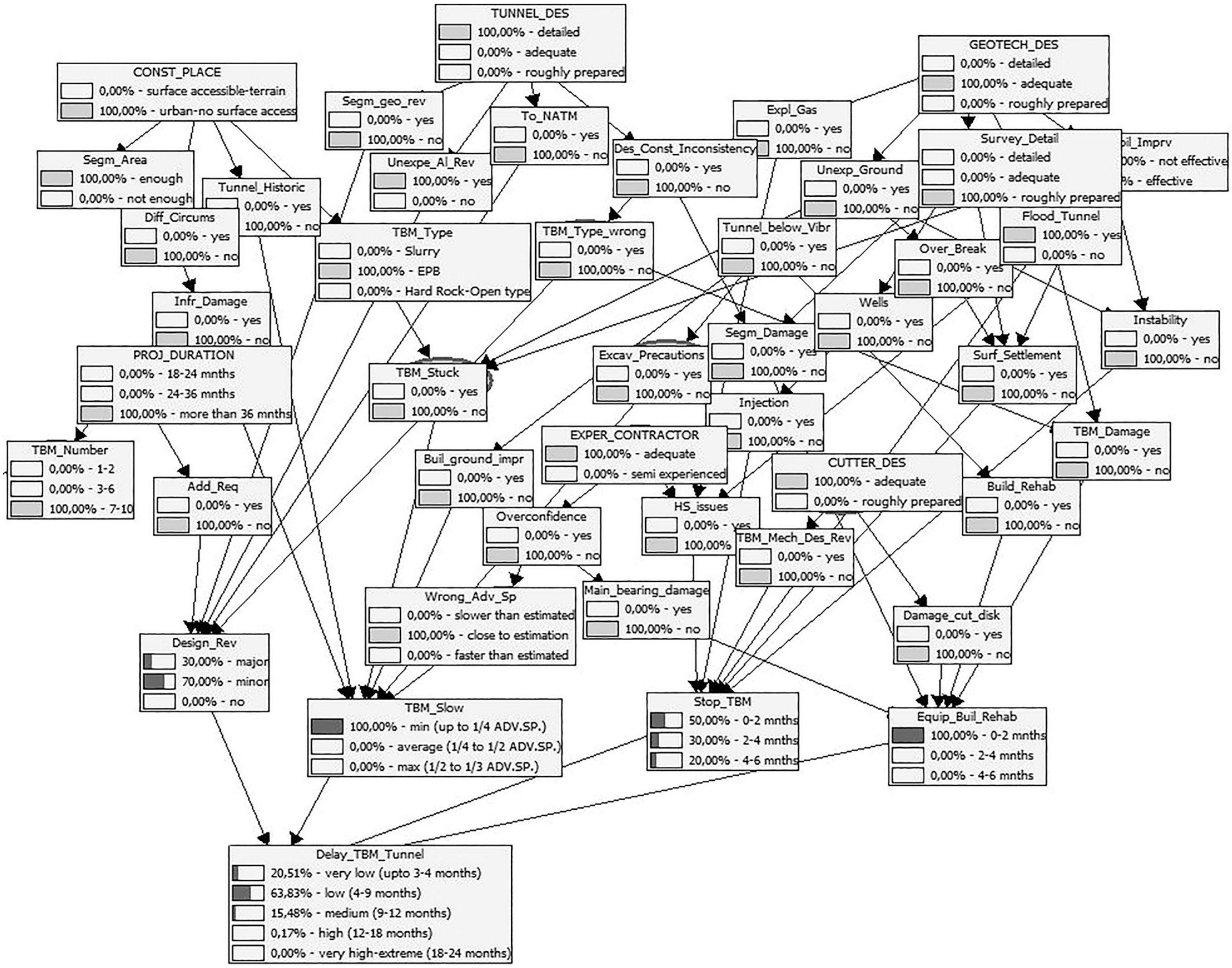

Fig. 7. BBN model for predictive validity test.

practitioners using the tool and reading the outputs would better understand the result that is predicted."

At this stage, the expert reviewed the structure of the tool and recommended some modifications in the user interface considering the third question. Previously only delay probabilities were provided in the "decision support" agent. The final structure is adequate and practicable in real systems for decision support purposes.

7.1.10. Historical data validation test

This test sought to assess whether the tool behaves as the model does and if the output data applied to the real case when a part of data required by the tool is entered [47]. This test was conducted to determine if the tool provides valuable information for a real case tunnel project. The input parameters of a finished TBM tunnel project were entered in BBN Tunnel with the expert using the "problem definition" agent of the tool. After the inference engine was run as depicted in Fig. 5, the delay risk probabilities for the project and predicted delay durations in the case of implementing six mitigation strategies were received from the "decision support" agent. The outputs generated from the tool were reviewed and discussed with the expert. The initial output of the tool was the predicted duration of the project, assuming that no strategies were implemented. Then, revised delay durations were calculated by the tool considering that six risk mitigation strategies were implemented (Table 9). The user could foresee the project's time overrun, the most important causes of delay, and the impact of strategies. It was seen that project delay could be decreased to 4.5 months when Strategy 1, which was about improving the geotechnical design level/maturity was applied.

Table 9
Results of historical data validation.

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

As a result of these tests, some modifications were done in the model and BBN Tunnel tool in the light of expert suggestions. Some additional boundary conditions were added in Extreme Conditions-Assumptions Verification Tests and the user interface of the BBN Tunnel tool was modified according to the Operational Face Validity Test. After ten tests that constitute the verification and validation methodology were carried out and modifications to the BBN model and the decision support tool were implemented according to expert judgements, the final BBN

Tunnel was found to conduct correct probabilistic calculations and produce reasonable outputs. However, it was also emphasized by experts that the decision-makers shall be aware of the fact that cost values regarding the strategies are average values and users of the tool are advised to carry out their own cost estimations specific to the target project rather than relying on only the cost values assumed by the tool.

7.2. Real case testing

The potential of the developed method to improve decision making in TBM tunnel projects was tested on a tunnel project. The project was an urban metro TBM tunnel construction in Istanbul, and the length of the tunnel was 18 km. It was actually constructed in 42 months using three TBM machines, whereas the estimated duration at the start of the project was 33 months. In order to test the performance of BBN Tunnel to predict a delay in this project and test whether the proposed strategies by BBN Tunnel are reasonable, the data was entered by the Company professionals that actually took part in the project.

Implementation of the real case project was conducted in a focus group discussion session with two experts. To start the implementation, data of the project were entered into BBN based risk assessment model. Evidence of each node was assigned to the model. Then the same data was entered into BBN Tunnel. This involved selection of project properties from the dropdown-box from the problem definition agent. These two data entry steps were implemented by the experts. Table 10 depicts the results gathered about the expected project delay and recommended strategy assignments. As it is described earlier, the decision support tool was created based on the sensitivity analysis results and only 20 of the 64 nodes in the computational model were used. Thus, the tool and model were expected to give different but close results on delay. Actually, in the case project, the BBN model predicted a delay of 8.4 months whereas BBN Tunnel predicted it as 8.8 months. The expected delay duration showed a 5% variance between the model and the tool, which is found acceptable.

The comparison of results calculated by the BBN Model and the BBN Tunnel decision support tool is summarized below. The experts highlighted the following points after investigating the results:

- The case project was actually completed with a 9-month delay, which is very close to the delay predicted by BBN Tunnel. The actual project delay duration showed 7% variance with the output of the BBN model and a 2% variance with the output of the BBN Tunnel tool. It has to be clarified that the model and the tool give different results as only the most significant risk factors found in sensitivity analysis were included in the BBN Tunnel. The prediction performance of the BBN based risk assessment model and BBN Tunnel were found satisfactory by the experts. It was stated by the experts that implementing the tool in the project initiation stage as well as in the project's course, would be useful to predict delays.

Table 10
Comparison of results in real case testing.

Output Data	Expected Delay - BBN Tunnel	Cost of strategies (% of Total Cost)
Strategy-0 Project – no strategies	8.8 months	–
Strategy-1 Improving geotechnical design level/maturity	7.8 months	3–7%
Strategy-2 Increasing health and safety precautions	8.5 months	5–8%
Strategy-3 Minimizing design revisions	4.3 months	5–10%
Strategy-4 Minimizing variation in TBM advance rate	6.8 months	8–12%
Strategy-5 Partial control	4.1 months	12–18%
Strategy-6 Full control – multiple strategies	3.4 months	15–38%

- When the changes in predicted delay values for different strategies were examined, strategy 3 was identified as the most preferable choice. Considering the risk factors experienced in the case project, minimizing design revisions was found as a reasonable strategy. Strategies 5 and 6, which were more expensive options were also found to have the potential to decrease delay. The experts found the strategy recommendations reasonable and noted that findings on impacts of strategies on expected delay risk provide valuable information for decision-makers. For example, if there were high public/employer pressure to speed up the project, strategies 5 and 6 could be used.
- The cost effects of the mitigation strategies were also discussed with the experts. They pointed out that it was highly valuable that the tool addressed the time and cost implications of strategies together. One negative issue raised by the experts about the risk mitigation aspect of the tool was that the cost data correspond to the metro tunnel projects carried out by the Company. Although the comparative cost percentages associated with six strategies adequately portray the relative impacts, other types of tunnel constructions would require adjustments in the actual cost percentages, or other companies willing to use the BBN Tunnel tool should consider adjusting strategies and their cost values according to their own experiences in previous projects.

8. Discussion of findings

After several verifications and validation tests, it has been demonstrated that the developed BBN Tunnel tool predicts the probability of completion of TBM tunnel projects within a specified time and supports the decision-making process during the formulation of risk mitigation strategies.

Considering the need in practice for reliable delay risk assessment in tunnel projects and the gap in the literature, the current study had two main objectives: to develop a comprehensive delay risk assessment method and develop a decision support tool for determining the most feasible strategies for handling delay risks in TBM tunnel projects. The risk assessment method was based on quantitative analysis of project uncertainties using BBN and based on a delay risk taxonomy. After several verification and validation tests, the developed BBN Tunnel tool predicts the probability of completion of TBM tunnel projects within a specified time and supports the decision-making process during the formulation of risk mitigation strategies.

The findings suggest that time overruns can be predicted by decision-makers with reasonable accuracy by using the developed BBN model and BBN Tunnel. The method not only provides the most important delay risk factors in tunnel projects, but also predicts delay under different risk mitigation strategies employed to decrease the risk of delay. When actual project delays were compared with the results acquired from the developed model and decision support tool, the variances were found satisfactory, and the experts found BBN Tunnel useful. However, the method performance highly depends on the data acquisition stage and validation procedures incorporated into the process. The accuracy of the delay prediction depends on the conditional relationships defined between risk sources and CPT assignments for risk factors.

Finally, it should be noted that the above discussions reflect the viewpoints of the experts that took part in the tool development process; thus, findings cannot be generalized. Moreover, the prediction capability of the tool cannot be validated by a single application. It should be used, and results should be compared with actual delay values to check its reliability and make necessary adjustments in the BBN model, if found necessary.

9. Conclusions

This study presents a delay risk taxonomy specific for TBM tunnel projects, systematic delay risk assessment methodology incorporating

BBNs, a comprehensive risk model that considers interdependencies between risk factors, and a decision support tool, BBN Tunnel for delay prediction that can help formulate cost-effective risk mitigation strategies to minimize time overruns in tunnel projects. Previous studies on tunnel risk management were based on analysis models focused on mainly geotechnical risks. On the other hand, the research provides a tunnel delay risk taxonomy and a BBN model-based assessment method that considers all potential delay risk factors involved in tunneling projects.

Moreover, the study also allows investigation of the impact of risk mitigation measures on the delay, which has been ignored in previous works. Testing of the model and the tool in a real project provides promising results in terms of its prediction ability and suggested strategies. The theoretical contribution is achieved by creating a meta-framework of risk identification, assessment, and mitigation process and delaminating the boundaries for theoretical applicability. Utilization of BBNs is usually difficult as tedious data collection and probabilistic calculations are necessary, whereas necessary background on probability theory is usually not available within the companies. This study showed how practical tools, such as BBN Tunnel, can be developed based on BBN models that can be easily used by decision-makers. The verification and validation methodology that was developed to ensure the reliability of BBN models and BBN-based tools can also provide guidelines for potential tool developers.

The risk taxonomy and model were developed by combining literature review findings with data achieved from the Company about previous projects. The information fed into the model about cause-effect relations and conditional probabilities that reflect Company experts' opinions cannot be generalized. It should also be noted that data gathering during the development of the computational BBN model involved many interviews and expert data-gathering sessions. This stage possessed difficulties due to the time and effort required to gather expert opinions on relations between parameters and the estimation of conditional probabilities. There are several approaches proposed in the literature to facilitate data collection for BBNs such as using statistical methods to determine relations between parameters and using algorithms [58,59].

In this research, due to the lack of a relevant database for the research problem, the only available source of information has been the domain experts in the tunneling field. Nevertheless, the methodology used in this research can be employed under different conditions and the developed BBN Tunnel can further be revised considering different company objectives, preferences and strategies. Companies can revise the developed BBN Tunnel tool considering the below suggestions.

1. The tunnel delay risk taxonomy developed in this study for TBM tunnels should be evaluated. In case the risk taxonomy is found fit for purpose, it can function as the basis of the BBN model. Otherwise, a tailor-made taxonomy and BBN model could be developed by the company carrying out a similar method as depicted in Fig. 1.
2. BBN Tunnel developed in this research can be used for predicting delays and assessing the impacts of different risk mitigation strategies. However, companies can integrate other decision-making perspectives into the tool such as quality, health and safety, and environmental impacts. Similarly, BBN Tunnel can also be revised by defining risk mitigation strategies other than the six strategies considered in this research.

The theoretical and practical contributions of this study can be summarized as:

- Considering the previous research on the subject, the developed method contributes to the knowledge base by; providing a novel method for project risk assessment for TBM tunnel projects incorporating Bayesian Networks, demonstrating how BBNs can be developed and validated by designing effective expert knowledge elicitation protocols and processes, creating a decision support tool for strategic risk assessment and delay prediction in TBM tunnel projects.
- For tunnel construction projects, the study provides practitioners an original and practical risk assessment model that considers interdependencies between risk factors, a decision support tool that can help to formulate effective risk mitigation strategies to minimize delay in tunnel projects considering the cost of strategies and their impact on delay, demonstrates how the method can be implemented in a construction company for strategic risk assessment.

Although the taxonomy, model, and tool have the potential to be used for delay risk assessment for tunnel projects and to enhance the decision-making process in project risk assessment, research also has certain improvement areas. For example, optimization algorithms could assist in finding the optimum strategy (considering multiple criteria such as cost, effectiveness, and duration) for the decision-makers. BBN model could help estimate cost overrun as well as delay by incorporating a cost overrun risk taxonomy. The BBN model can be used in a follow-up study, where it is implemented in real projects from their early stages till the end and then, how it can function as a decision support tool to minimize delay in a project's life cycle can be monitored. An intelligent BBN model can be developed by updating the conditional probability values considering the lessons learned in real projects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge the support received from Cem Tutyol, Is Cozum Bilisim for the development of the decision support tool in this research, the Turkish construction company which supported this research by providing the case study data and all experts who attended the EKE sessions.

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