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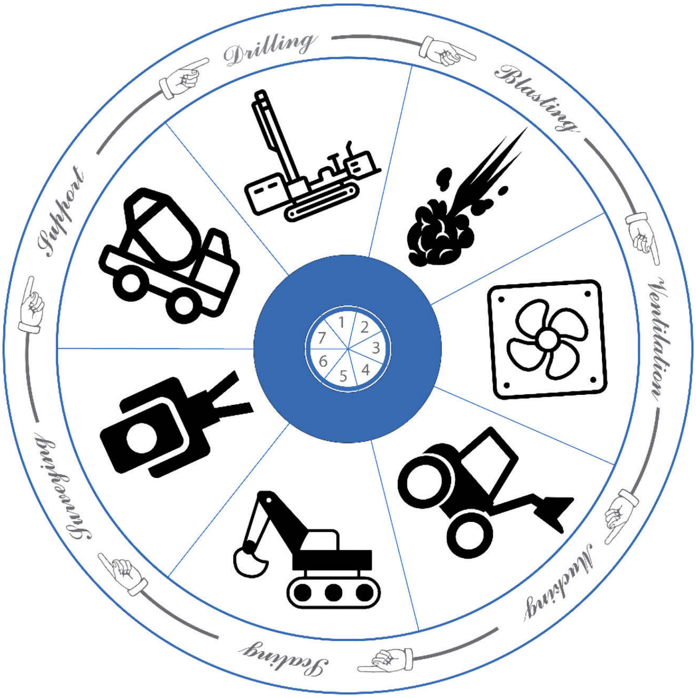

RISK MANAGEMENT IN TUNNELING PROJECTS: ESTIMATION AND PLANNING

Mohammad Mohammadi

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Riskhantering i tunnelprojekt: Uppskattning och planering

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PREFACE

The primary objectives of tunneling and infrastructure projects revolve around completing the project while meeting the required quality standard, within the specified time frame and adhering to the allocated budget Tunneling projects, given their substantial scale, are particularly vulnerable to financial losses resulting from delays in completion. Additionally, inaccurate cost estimations during the planning stage can lead to significant financial setbacks and, in some cases, even bankruptcy among project participants. It is equally important to consider the financial repercussions of necessary repairs or corrective actions due to quality issues during the planning- and construction phases.

In this work, carried out as a PhD project at the Division of Soil and Rock Mechanics, KTH Royal Institute of Technology, Stockholm, a conceptual risk model has been formulated specifically for the purpose of enhancing time and cost estimations in tunneling projects. This risk model serves as a tool to scrutinize and contrast existing probabilistic time and cost estimation models for tunnel projects, aiming to identify potential areas for improvement.

The doctoral student Mohammad Mohammadi was supervised by Johan Spross, Stefan Larsson, Fredrik Johansson, and Anna Kadefors, all at KTH. The members of the reference group were Peter Lundman, Miriam Zetterlund, Claes Mellqvist, Johan Brantmark, Robert Sturk, Stig Eriksson, Gösta Ericson, Håkan Stille, Per Tengborg and Patrik Vidstrand and the research project was funded by BeFo, Formas (grant 2017-01218) and KTH.

Stockholm

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FÖRORD

De primära målen för infrastrukturprojekt kretsar kring att slutföra projekten med erforderlig kvalitetsstandard, inom den angivna tidsramen och i enlighet med den tilldelade budgeten. Stora tunnelprojekt är särskilt känsliga och påverkas ekonomiskt direkt till följd av förseningar. Dessutom kan felaktiga kostnadsuppskattningar under planeringsstadiet ge betydande ekonomisk påverkan och, i vissa fall, till och med orsaka konkurs hos projektdeltagare. Det är också viktigt att överväga de ekonomiska konsekvenserna av nödvändiga reparationer och underhållsåtgärder som har sin grund i brister under planerings- och byggfasen.

I detta arbete, som utförts som ett doktorandprojekt vid Avdelningen för jord- och bergmekanik vid KTH, Stockholm, har en konceptuell riskmodell tagits fram specifikt i syfte att förbättra tids- och kostnadsuppskattningar i tunnelprojekt. Denna riskmodell fungerar som ett verktyg för att granska och kontrastera befintliga probabilistiska tids- och kostnadsuppskattningsmodeller för tunnelprojekt, i syfte att identifiera potentiella förbättringsområden.

Doktoranden Mohammad Mohammadi handleddes av Johan Spross, Fredrik Johansson, Stefan Larsson och Anna Kadefors, samtliga vid KTH. Referensgruppens medlemmar var Peter Lundman, Miriam Zetterlund, Claes Mellqvist, Johan Brantmark, Robert Sturk, Stig Eriksson, Gösta Ericson, Håkan Stille, Per Tengborg och Patrik Vidstrand och forskningsprojektet finansierades av BeFo, Formas (nr. 2017-01218) och KTH.

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SUMMARY

Cost overruns and schedule delays are frequently observed occurrences in the construction of transport infrastructure projects. Such phenomena lead to the mismanagement of significant amounts of both public and private resources. An examination of the literature reveals that uncertainty stands out as one of the potential primary causes of cost overruns and schedule delays. To address the impact of uncertainty on time and cost estimations in transport infrastructure projects, probabilistic approaches can be employed.

In this work, a conceptual risk model has been formulated specifically for the purpose of enhancing time and cost estimations in tunneling projects. This risk model serves as a tool to scrutinize and contrast existing probabilistic time and cost estimation models for tunnel projects, aiming to identify potential areas for improvement. Furthermore, the conceptual model is utilized to delve into the factors influencing the accuracy of subjective assessments regarding the input parameters in time estimation models. It also explores methods for incorporating the role of tunneling phases into the subjective assessment of these input parameters.

Then, enhancements and updates are introduced to the existing KTH model, which primarily target the three main sources of uncertainty in time- and cost estimation for tunneling projects. These sources encompass variability in construction performance, geological uncertainties, and the potential incidence of disruptive events. The analysis and improvements related to construction performance involve three sequential steps. In the first step, the construction process is modeled using the work breakdown structure (WBS), enabling a more realistic assessment of tunneling time. Subsequently, in the second step, PERT distributions are employed to model the uncertainty in the duration of unit activities, compared to the commonly used triangular distributions. The third step involves a detailed ex- amination of a real tunnel project's data to identify components contributing to construction performance variability for unit activities. This analysis pinpoints three main components: typical performance variability, minor performance delays, and minor machinery delays. These components are integrated into the KTH model, resulting in its further update concerning construction performance variability.

The novel approach is introduced into the KTH model by leveraging the Metropolis-Hastings (MH) algorithm within the framework of Markov Chain Monte Carlo (MCMC) simulation to address geo- logical uncertainties along the tunnel route. This method enhances field diversity, facilitates round-by-round simulation of the tunneling process, and allows the model to accommodate uncertainty in the critical path for tunneling projects involving multiple headings. These enhancements aim to improve decision-making processes and mitigate risks associated with schedule delays and cost overruns. Additionally, disruptive events are now modeled as stochastic variables, an improvement on the original version of the KTH model.

Keywords: Cost overrun, Transport infrastructure projects, Time and cost estimation, Probabilistic approaches, Tunneling

SAMMANFATTNING

Kostnadsöverskridanden och förseningar i tidplanen inträffar ofta vid byggande av transportinfrastrukturprojekt. Detta leder till slöseri av betydande resurser, både offentliga och privata. En genomgång av litteraturen visar att osäkerhet framträder som en av de potentiella primära orsakerna. För att hantera påverkan av osäkerhet på tid- och kostnadsuppskattningar i transportinfrastrukturprojekt kan probabilistiska metoder användas. I denna doktorsavhandling utarbetades först en konceptuell riskmodell som kan förbättra tid- och kostnadsuppskattningar specifikt i tunnelprojekt. Riskmodellen användes som ett verktyg för att granska och jämföra olika befintliga probabilistiska modeller för sådana skattningar, i syfte att identifiera möjliga förbättringsområden. Riskmodellen användes också för att undersöka faktorer som påverkar noggrannheten i subjektiva bedömningar av indata i tidsuppskattningsmodeller. Även metoder för att inkludera olika tunnelbyggnadsfaser i den subjektiva bedömningen av dessa indata utforskades.

Forskningen har resulterat i förbättringar och uppdateringar av den befintliga KTH-modellen för tid- och kostnadsuppskattning i tunnelprojekt. Modellen inriktar sig mot tre huvudsakliga källor till osäkerhet i skattningen: variabilitet i arbetsprestation, geologisk osäkerhet och förekomst av försenande händelser. Analysen och förbättringarna av modelleringen av arbetsprestation utfördes i tre steg. I det första steget modellerades byggprocessen med hjälp av en så kallad Work Breakdown Structure (WBS), vilket möjliggör en mer realistisk bedömning av tunnelprojektets byggtid. I det andra steget användes PERT-fördelningar för att modellera osäkerheten i tidsåtgång för de olika aktiviteterna i produktionscykeln, istället för den annars ofta använda triangelfördelningen. Det tredje steget utgjordes av en detaljerad undersökning av data från ett verkligt tunnelprojekt för att identifiera vilka komponenter som bidrar till variabiliteten i arbetsprestation i produktionscykelns olika aktiviteter. Denna analys pekar ut tre huvudkomponenter: typisk variabilitet i arbetsprestation, mindre prestationsförseningar och mindre maskinförseningar. Dessa komponenter integrerades i KTH-modellen, vilket resulterade i ytterligare uppdateringar avseende variabiliteten i arbetsprestation.

En ny metod infördes i KTH-modellen genom att använda Metropolis-Hastings-algoritmen inom ramen för Monte Carlo-simulering med Markovkedjor, för att hantera geologiska osäkerheter längs tunnelsträckningen. Denna metod möjliggör stegvis simulering av tunnelbyggnadsprocessen så att KTH-modellen nu kan beakta osäkerhet i kritiska linjen i tunnelprojekt med flera fronter. Dessa förbättringar syftar till att underlätta beslutsfattandet och minska riskerna för förseningar och kostnadsöverskridanden. Dessutom är det nu möjligt att modellera storleken på försenande händelser som stokastiska variabler, vilket är en annan förbättring jämfört med den ursprungliga versionen av KTH-modellen.

Nyckelord: Kostnadsöverskridande, Transportinfrastrukturprojekt, Tids- och kostnadsuppskattning, Probabilistiska metoder, Tunnelbyggnad

CONTENTS

1. INTRODUCTION

1.1 Research motivation

Urbanization and the growing density of cities are driving an escalating demand for transportation infrastructure. With limited available ground space in urban areas, conventional road and rail networks restrict the free movement of both people and animals, while also contributing to environmental problems like pollution and noise. To address these pressing transportation challenges, societies must increasingly explore the utilization of underground spaces.

The primary objectives of tunneling and infrastructure projects revolve around completing the project while meeting the required quality standard, within the specified time frame and adhering to the allocated budget [1]–[3]. Tunneling projects, given their substantial scale, are particularly vulnerable to financial losses resulting from delays in completion. Additionally, inaccurate cost estimations during the planning stage can lead to significant financial setbacks and, in some cases, even bankruptcy among project participants. It is equally important to consider the financial repercussions of necessary repairs or corrective actions due to quality issues during the planning and construction phases.

The overall duration and cost of tunneling projects are influenced by the geological conditions along the tunnel route [4], [5]. Often, there is a lack of geological information available before construction commences, and tunnel owners as well as contractors tend to underestimate or overlook geological risks. This negligence often leads to project delays and budget overruns [6], [7]. Notable examples of tunneling projects where such risks were disregarded include the Channel tunnel between France and the UK [8] and the Hallandsås Tunnel in Sweden [9], [10]. In both cases, substantial public or private resources had to be allocated to address the consequences.

Furthermore, inadequate risk allocation within project contracts often leads to poor risk assessment and, subsequently, lengthy and costly disputes. In some instances, it has even resulted in contractor bankruptcies. To establish a foundation for long-term sustainable underground infrastructure and ensure fair risk-sharing among all involved parties, it is imperative to recognize the inherent variability in geological conditions (herein typically included in the term uncertainty). This necessitates the development of new methods for assessing and communicating geological information throughout all project phases, along with adaptable construction approaches and innovative contracting models.

1.2 Objectives

The purpose of the research presented in this report is to establish a framework that streamlines the process of risk-based time and cost estimations for tunneling projects. This framework should effectively incorporate the uncertainties linked to the geological conditions at the site and the variation in construction time and cost associated with the construction methods employed.

The objectives are:

- To investigate the impact of uncertainty on project performance and identify methodologies suitable for addressing uncertainty during the early project phases.

- To assess the current state of existing models for probabilistic time and cost estimation in tunneling projects, pinpointing areas where potential enhancements can be made.

Following that, the central goals encompass:

- To enhance and update existing models for time and cost estimation.
- To improve modelling of input parameters, ensuring a comprehensive representation for improved modeling accuracy.
- To showcase the practical applications of the updated modeling through real-world case examples, providing concrete illustrations of the advancements and their impact.

1.3 Methodology

Initially, a literature review was conducted to examine the issue of time and cost overruns in transport infrastructure projects. This review highlighted a common neglect of the influence of uncertainty in explaining project overruns. To address this, probabilistic methodologies capable of accommodating uncertainty in time and cost estimations for construction projects were explored. Following that, a subsequent review of literature delved into probabilistic methodologies tailored to tunneling projects, analyzing existing models.

The purpose of this analysis was to identify areas where these existing models could be enhanced. The intention was to incorporate these findings into the model developed by Isaksson and Stille [5] (the KTH model), ultimately resulting in its improvement and update. This comprehensive study led to the development of a conceptual risk model for time and cost estimation. The result is presented in detail in Mohammadi et al. [11] and Mohammadi and Spross [12]. Subsequently, the KTH model was updated based on the recognized improvement opportunities, namely concerning geological uncertainties (in [13], [14]), construction performance variability (in [13], [15], [16]), and disruptive events (in [13], [14]). In addition The Markov Chain Monte Carlo simulation is incorporated in the model as the means of calculations to more accurately account for uncertainties in the results. The application of the updated model is demonstrated in these studies using real-world case examples.

1.4 Limitations

This research concentrates on the development and implementation of a model specifically designed for time estimation, considering uncertainties related to geology, construction, and occurrence of disruptive events. Two limitations arise in the development of this model:

- Acquiring detailed cost data poses a significant challenge due to the confidential nature of such information, often guarded by owners for competitive bidding purposes. Consequently, although the model can be adjusted for cost estimation, all the case examples presented in this report specifically focus on time estimation.
- Validation of modeling results poses an immense challenge, demanding access to data from a substantial number of tunneling projects for comparison with the model's outcomes. While not entirely impossible, the realization of this verifica-

tion is highly unlikely due to the confidential nature of the data held by project owners.

2. TIME AND COST OVERRUN

2.1 Background

2.1.1 The status of overrun

Project delays and cost overruns, also referred to as cost escalation, are pervasive challenges within the global construction industry [17], [18]. The standard international definition quantifies overrun as the actual costs minus the estimated costs, expressed as a percentage of the estimated costs [19]–[21]. A comprehensive study by Flyvbjerg et al. [20], involving a large sample of projects across 20 nations and five continents, demonstrated that nine out of ten projects experienced cost overruns.

Numerous researchers have dedicated their efforts to investigating the phenomena of cost overruns and time delays. A review of the existing literature reveals that the majority of these studies have attempted to pinpoint the primary causes of these occurrences. They have done so either through surveys distributed to industry experts [22]–[28] or through statistical analysis of extensive project data [29]–[32]. In both approaches, researchers have identified a multitude of contributing factors, including scope changes, project complexity, construction delays, unrealistic estimations, and numerous others as reasons for cost overruns. In some instances, like the studies conducted by Aljohani et al. [33] and Mahamid and Dmaidi [25], the number of identified factors reached as high as 173 and 41, respectively.

Given the diverse array of potential triggers for these issues, some researchers have attempted to categorize these factors into groups, such as internal or external factors [34]. Flyvbjerg [35], however, posits that all factors, including scope changes and project complexity, contribute to cost overruns at various stages of a project's lifecycle, but they are not the fundamental or root causes. He argues that the root cause lies in project planners systematically underestimating or disregarding the risks associated with scope changes and project complexity during project development and decision-making processes. Additionally, Flyvbjerg [35] contends that the concept of decision-makers' escalating commitment to an inefficient course of action, often termed "lock-in" [36], is not a root cause, as it is a common occurrence in major projects, and planners should consider the risk of its manifestation.

In the context of transportation infrastructure projects, Flyvbjerg et al. [19], Flyvbjerg et al. [20], and Flyvbjerg et al. [21] have conducted influential studies on cost overruns. These studies have identified several crucial factors impacting overruns, including project size, geographical project location, project type, project duration, and ownership structure. Consequently, the results of their research are summarized here. Subsequently, other researchers have explored the effects of these factors on various project samples [30], [37]–[40], and their findings are discussed in the pertinent subsections.

2.1.2 Effect of project type

Flyvbjerg et al. [19] and Flyvbjerg et al [20] conducted an analysis using a dataset of 258 transport infrastructure projects to explore the impact of project type on the extent of cost overruns. They categorized the projects as follows:

- Rail projects, comprising a total of 58 projects, encompassing high-speed, urban, and conventional inter-city rail endeavors.

- Fixed link projects, consisting of 33 projects, which included tunneling and bridge construction.

- Road projects, totaling 167 highway and freeway projects.

Their rigorous statistical analysis yielded highly significant results, revealing differences between estimated and actual costs, signifying cost overruns for all project types. On average, rail projects experienced a 44.7% cost difference, fixed link projects incurred a 33.8% difference, and road projects had a 20.4% difference. This analysis also demonstrated that the influence of project type on cost overruns is statistically significant. Further examination of the data revealed that high-speed rail projects had the highest percentage of cost underestimation within the first category of project types, followed by conventional rail projects. In the second category, tunneling projects exhibited higher degrees of cost underestimation compared to bridges, indicating that technological complexities and geological uncertainties might contribute to cost overruns. (Geological uncertainty is a broad term used in much of the scientific literature. It includes uncertainty related to presence of various geological features, as well as uncertainty about geotechnical properties and hydrogeological conditions.)

In a separate study by Odeck [40] on Norwegian road construction projects, it was concluded that project type (road, bridge, tunnel) did not significantly affect cost overruns. However, Cantarelli et al. [38] found that project type did matter for the magnitude of cost overruns in Dutch transport infrastructure projects, with fixed link projects experiencing the largest average overrun. Further examination within the fixed link category in Dutch projects revealed that tunnels were more susceptible to cost overruns than bridges.

Locatelli et al. [39] also identified that the risk of delays in tunnels and rail projects was higher during the construction phase, and the construction of underground structures could lead to cost overruns in this phase. Regarding project type, Huo et al. [30] reported that rail projects experienced the most significant cost escalation, followed by fixed link projects, while road projects had the lowest rate of overrun in Hong Kong's transport infrastructure mega-projects.

2.1.3 Cost overrun by geographical location

Flyvbjerg et al. [19] and Flyvbjerg et al. [20] utilized a diverse sample encompassing projects from various regions, including Europe, North America, and other geographical areas, such as Japan and a group of ten developing countries. Their analysis revealed a highly significant variation in cost underestimation across different geographical locations, underscoring the significance of geographical location as a contributing factor to cost overruns. However, when examining the data separately for Europe and North America, the difference between these two regions was found to be statistically insignificant. Consequently, it was deduced that the substantial variations in geographical location primarily stemmed from the "other geographical areas" category.

2.1.4 Effect of project size

In their study, Flyvbjerg et al. [21] employed the same dataset of 258 projects to investigate whether the project's size is correlated with the extent of cost overruns. They used forecast costs as the measure of project size for two key reasons:

- Statistically, cost overruns are intertwined with the actual construction costs, making it necessary to use forecast costs as a more robust measure.
- Forecast construction costs serve as the foundation for determining whether a particular project should proceed.

Their analysis indicated the need to treat project types separately. The results demonstrated that for fixed link projects, which encompass tunnels and bridges, there is an almost significant statistical relationship between cost overruns and project size. However, for road and rail projects, there was no evidence to suggest that cost escalation depended on project size. To enhance the analysis, they also excluded outlier projects with implementation duration of 13 years or longer. This led to the conclusion that there is a significant association between project size and cost escalation for fixed link projects, with larger projects experiencing more substantial cost escalations.

In contrast, Odeck [40] found that cost overruns were more prevalent in smaller projects within the Norwegian road construction sector. A similar conclusion was reached by Cantarelli et al. [38] in the context of Dutch infrastructure projects. It is worth noting that while small projects may have a higher average overrun, large projects still contribute significantly to the total overrun due to their size. Furthermore, according to Huo et al. [30], there is no significant dependency between project size and cost overruns for megaprojects in Hong Kong's transport infrastructure sector.

2.1.5 Effect of project sluggishness

The inherent sluggishness in the preparation, planning, authorization, and evaluation processes of large infrastructure projects often poses significant challenges to project implementation. The duration of the implementation phase, defined as the period from the decision to initiate construction to the completion of construction and the commencement of operations, plays a crucial role in influencing cost escalation. Empirical evidence established that the length of the implementation phase has a highly significant impact on cost escalation, particularly for projects with a duration of less than 13 years. Projects that exceeded this 13-year threshold were considered statistical outliers and were not included in the analysis. Among the total sample of 258 projects, information regarding the duration of the implementation phase was available for 111 projects (38 rail, 33 fixed link, and 40 road projects)[21].

Additionally, the analysis revealed variations in the length of the implementation phase across different project types, with fixed link projects, encompassing tunnels and bridges, having the longest duration [21]. Further dissection of this phase into pre-construction and construction phases [37], [38] revealed that the length of the pre-construction phase significantly influences cost overruns in Dutch transport infrastructure projects, whereas the length of the construction phase exerts less influence on cost overruns. In contrast, Huo et al. [30] determined that the relationship between the length of the pre-construction phase and cost overruns was significant for road projects, but not for rail and fixed link projects. Furthermore, they concluded that the duration of the construction phase did not significantly affect cost overruns.

2.1.6 Effect of type of ownership

To examine the impact of project ownership type on cost escalation, Flyvbjerg et al. [21] categorized ownership as follows:

- Private ownership
- State-owned enterprise, referring to corporations owned by the government and organized in compliance with company laws, such as incorporated or limited companies.
- Other public ownership, representing the conventional form of public ownership, where typically a government ministry owns the project, and it is reflected in the public budget.

In their statistical analyses, these three project ownership types were analyzed separately. The effect of ownership type on cost escalation in fixed link projects, encompassing tunnels and bridges, was found to be statistically significant. Among these, state-owned enterprises exhibited the highest average cost overrun at 110%, while privately owned and other publicly owned fixed link projects had average cost overruns of 34% and 24%, respectively. The analysis of variance indicated a significant disparity in cost overruns among fixed link projects based on ownership type. However, this analysis did not provide finer distinctions, such as whether the differences could be attributed to dissimilarities between tunnels and bridges, or other factors previously investigated, e.g. size of project.

2.1.7 Cost overruns over time

Based on a thorough statistical analysis of a dataset comprising 258 projects, the findings by Flyvbjerg et al. [19] and Flyvbjerg et al. [20] indicate that cost overruns in transport infrastructure projects have remained largely consistent over an extensive duration, spanning approximately 70 years. In their analysis, they were unable to reject the null hypothesis, suggesting that the year of the decision-making process did not exert a significant influence on the discrepancy between estimated and actual project costs. This same pattern held true for the year of project completion. Consequently, they concluded that there has been no reduction in cost overruns over this 70-year timeframe, which they suggest indicates that the underestimation of costs may be a deliberate phenomenon.

2.2 Explanation of time and cost underestimations

Flyvbjerg et al. [19] provided insights into cost underestimations by categorizing them into four types of explanations: technical, economic, psychological, and political. They conducted an in-depth examination of these explanations to identify which one aligns most closely with their dataset.

2.2.1 Technical explanations

Technical explanations for cost overruns typically revolve around forecasting errors, including the use of imperfect estimation techniques, insufficient data, mistakes made by forecasters, inherent challenges in predicting the future, and the lack of forecaster experience. As highlighted by Flyvbjerg et al. [19], if these technical inadequacies were indeed the primary reasons behind inaccurate forecasts, one would anticipate that the distribution of percentage cost overruns would exhibit less bias around zero. However, their analysis led to a statistically significant conclusion that the distribution of percentage cost overruns in their sample of 258 projects possessed a non-zero mean.

Furthermore, if factors such as the utilization of imperfect techniques, data inadequacies, and forecaster inexperience were the primary drivers of cost underestimations, one would expect forecasting accuracy to improve over time as errors and their sources became more evident and were addressed. Consequently, Flyvbjerg et al. [19] concluded that technical explanations were not aligned with their dataset in elucidating cost overruns.

2.2.2 Economic explanations

Economic explanations for cost underestimations encompass two categories: economic self-interest and public interest considerations. In terms of economic self-interest, approving a project generates employment opportunities for engineers and construction companies, allowing stakeholders to potentially profit from it. Consequently, if these stakeholders have the means to directly or indirectly influence the forecasts, it could lead to outcomes favoring project construction.

From a public interest perspective, project proponents may intentionally underestimate project costs to incentivize officials to conserve public resources. According to this rationale, higher cost estimates could potentially encourage wasteful spending of taxpayer funds by contractors. Both forms of economic explanations align well with empirical data and can provide a plausible explanation for the consistent cost underestimations observed in transport infrastructure projects [19].

2.2.3 Psychological explanations

Psychological explanations, which focus on the inherent biases in the mental perspectives of forecasters and project proponents, offer insights into cost underestimations. Within this framework, forecasters and promoters tend to exhibit excessive optimism regarding project outcomes during the planning phase, a phenomenon known as "appraisal optimism." This optimism naturally results in estimated costs being lower than the actual costs.

While appraisal optimism can contribute partially or even entirely to cost underestimations, its impact becomes more pronounced when forecasters lack extensive experience. However, it appears unlikely that forecasters consistently made the same optimistic error over decades without learning from their mistakes. This learning process should have led to a reduction or elimination of forecasting bias over time, ultimately improving estimation accuracy. Consequently, psychological explanations do not appear to be the primary cause of cost underestimations in transport infrastructure projects [19].

2.2.4 Political explanations

The political explanation revolves around the intentional deception of investors through cost underestimations. In this scenario, forecasters deliberately underestimate project costs while inflating the expected benefits to enhance the likelihood of project approval and initiation. Additionally, the "everything-goes-according-to-plan" (EGAP) principle can be seen as a form of deception, as it entirely disregards the risk of cost escalation due to factors like project changes, delays in project duration, and unforeseen accidents. This explanation gains support from the data analyzed by Flyvbjerg et al. [19], where 86% of the projects within their sample of 258 experienced cost overruns.

Flyvbjerg et al. [19] evaluated the four categories of explanations for cost overruns in terms of whether they stemmed from error or deliberate deception. Technical and psychological explanations were attributed to errors, while economic and political explanations were linked to deliberate deception. Since they [19] believed economic and political explanations to be the primary drivers of cost overruns, they concluded that deliberate lying and deception are the primary factors contributing to the recurrent occurrence of cost overruns in transport infrastructure projects.

2.3 Discussion on the literature

2.3.1 Importance of technical explanations of cost overrun

Flyvbjerg et al. [19] dismissed technical reasons as a primary factor contributing to cost overruns for several reasons. First, they pointed out that the distribution of cost overruns within their sample of projects did not center around zero, indicating that more projects experienced cost overruns than cost underruns. In fact, a staggering 9 out of 10 projects in their sample encountered cost overruns. However, it is worth questioning their conclusion to reject technical explanations solely based on this bias, as there are three other categories of explanations—economic, psychological, and political—that can also influence forecasting outcomes. Therefore, even if technical methods had improved over time, the distribution of overruns in a representative sample of projects could still be skewed away from zero due to the influence of these other factors. It is especially challenging to disentangle the separate effects of these factors within their sample or any other sample, for that matter.

Moreover, the representativeness of the project sample utilized by Flyvbjerg et al. [19] is questionable. While it is the largest sample of its kind, it does not represent the full spectrum of transport infrastructure projects worldwide. In their sample of 258 projects, there were only 33 fixed link projects, encompassing tunnels and bridges, while the majority of the sample consisted of road projects (167 projects). Not only is the number of fixed link projects limited, but it is also crucial to recognize that the construction processes for bridges and tunnels, although categorized as fixed links, differ significantly. These distinctions in construction processes can profoundly impact project outcomes in terms of both time and costs.

Another issue to consider in rejecting technical explanations is the influence of unforeseen problems, such as geological, environmental, and safety concerns, which essentially are risks. Risk, defined as the effect of uncertainty on project objectives [41], includes the impact of uncertainty on cost overruns, which should be carefully assessed for each project. Flyvbjerg et al. [19] discuss the effect of risk on cost overruns in their analysis:

> “We may agree with proponents of technical explanations that it is, for example, impossible to predict for the individual project exactly which geological, environmental, or safety problems will appear and make costs soar. But we maintain that it is possible to predict the risk, based on experience from other projects, that some such problems will haunt a project and how this will affect costs. We also maintain that such risk can and should be accounted for in forecasts of costs, but typically is not. For technical explana-

> tions to be valid, they would have to explain why forecasters are so consistent in ignoring cost risks over time, location and project type" (p. 287).

This discussion does not substantiate the conclusion that technical factors are incapable of explaining cost underestimations. Quite the opposite, the recurrent neglect of risk by forecasters underscores the significance of technical explanations and highlights their importance in any endeavor to account for cost underestimations.

Recent studies indicate that forecast accuracy has indeed shown signs of improvement over time. For instance, Gao and Touran [29] observed that the precision of cost estimates during the decision-making phase has increased for U.S. rail transit projects. Similarly, Miranda and Renneboog [42] determined that cost deviations in Portuguese public infrastructural investment projects have demonstrated improvement over time. In contrast to the rationale put forth by Flyvbjerg et al. [19] and Flyvbjerg [43], Miranda and Renneboog [42] concluded that this enhanced accuracy in cost estimations stemmed from the benefits of experiential learning rather than the introduction of new procurement laws.

Dantata et al. [44] also found evidence of a positive trend in forecast accuracy improvement within U.S. rail transit projects. Additionally, Makovšek [45] reported that cost performance has ameliorated over time for projects undertaken between 1995 and 2007 as part of the National Highway Construction Program in Slovenia. Another key observation made by Makovšek [45] was that technical factors were the primary cause of systematic cost overruns in Slovenian highway projects.

In light of the discourse presented in this section, it is imperative to assert that technical explanations carry equal significance alongside other explanatory factors and should not be overlooked when seeking to elucidate cost escalations in transport infrastructure projects.

2.3.2 Other explanations of cost overrun

The other three categories of explanations encompass psychological, economic, and political rationales. As previously mentioned, Flyvbjerg et al. [19] classified all the factors contributing to cost overruns as falling into either the category of "error" or "deception." According to their framework, technical and psychological factors are categorized as errors, while economic and political factors are seen as instances of deliberate dishonesty and deception. In their original analysis[19], they concluded that it is the deliberate deception, namely economic and political explanations, that predominantly explains project cost overruns, while psychological factors are of lesser importance, as they could be addressed through learning over an extended period.

However, Flyvbjerg [43] later revised this stance, asserting that strategic misrepresentation (economic-political explanations) and optimism bias (psychological explanations) are the primary contributors to cost overruns. He argued that these factors complement each other rather than compete with each other. To mitigate these issues, he introduced the concept of reference class forecasting.

Nonetheless, Love and Ahiaga-Dagbui [46] conducted a critical examination of the work of Flyvbjerg et al. [19] and characterized the conclusions of this research as akin to misinformation or "fake news". In response to [46], Flyvbjerg et al. [47] offered further discussions and clarification of their original findings.

Each project possesses its own unique set of circumstances, rendering the task of conducting statistical analyses on large project samples exceedingly intricate. Any attempt to draw definitive conclusions from such analyses of a broad range of infrastructure projects is susceptible to yielding erroneous findings regarding the causes of cost overruns. Consequently, project-specific variables constitute a crucial component of research on cost overruns, an aspect often overlooked in prior studies. Furthermore, the reality of cost underestimation in transport infrastructure projects is nuanced. Technical, psychological, and economic-political explanations for cost overruns are not in competition but rather complement each other. The relative importance of each explanation hinges on the specific circumstances inherent to a given project.

2.3.3 Does uncertainty explain cost overrun?

The primary concern within the technical explanation for time and cost overruns revolves around the anticipation of potential issues, including geological, environmental, and safety challenges—essentially, the management of risk. During the project's planning phase, uncertainties regarding the geological conditions (particularly in tunneling projects), environmental factors, and safety issues prevail, making it very difficult for forecasters to predict these aspects with a high degree of accuracy. Given the inherent uncertainty surrounding these issues, there is good reason to employ risk management methodologies to address them effectively.

Utilizing probabilistic approaches for estimating the time and cost of transport infrastructure projects is a more appropriate method than deterministic ones, according to [7], [48], [49]. In such cases, the estimation outcome comprises a probabilistic distribution of time and cost, whereas the actual time and cost of the project are single values. Employing probabilistic estimation for project time and cost provides a more realistic perspective and renders the conventional concept of cost overrun less relevant. Comparing a single actual cost figure with a probabilistic distribution of estimated costs would be incongruous. In this context, the primary concern becomes the decision-making regarding risk tolerance or aversion by the involved parties, along with the project's financial circumstances. For instance, if the project owner has no alternative funding sources beyond a designated budget, they may choose cost estimates with higher probabilities of occurrence. Conversely, if additional financing options are available, such as profits from other projects, the project owner might opt for a lower cost estimate associated with higher inherent risk, i.e., a lower probability.

Several probabilistic approaches have been devised and employed for estimating the time and cost of tunneling projects. In Mohammadi et al. [11] and Mohammadi and Spross [12], a comprehensive review of the literature on this topic was conducted as a part of this research project, and the existing models were evaluated within the framework of the developed risk model. Additionally, the potential for enhancing these models to achieve a more realistic distribution of time and cost was explored. Consequently, further enhancements and updates are done concerning geological uncertainties, construction performance variability, and disruptive events on the model developed by Isaksson and Stille [5] (henceforth referred to as the KTH model). The practical applications and implications in each topic studied in this research project are presented in Mohammadi et al. [13], Mohammadi and Spross [15], Mohammadi et al. [16], and Mohammadi and Spross [14]. Chapter 3 serves as a summary, encapsulating the core improvements and updates of the KTH model.

3. KTH TIME ESTIMATION MODEL

In this chapter, the developed risk model and introduced enhancements and updates to the KTH model are outlined. Section 3.1 explains the original KTH model, providing a baseline for comparison with the updates presented in Section 3.2.

3.1 The original KTH model

3.1.1 Theoretical framework

The original KTH model was developed by Isaksson & Stille [5], [50] where the total time (T) and cost (C) are represented as the combination of normal and exceptional times and costs (T_{N}, C_{N}, T_{E}, and C_{E}). The initial step involves identifying potential geological and hydrogeological conditions expected along the planned tunnel route. Subsequently, the tunnel route is partitioned into n_{zone} geotechnical zones, each characterized by relatively similar geological conditions, where the same construction method is assumed to be applicable.

Calculation of tunneling time in the model is facilitated through the introduction of the parameter production effort, Q [h/m]. This parameter represents the time required for the construction of a unit length ($l = 1$ m) of the tunnel. The underlying assumption is that the parameter Q in tunnel section l is significantly influenced by the geological and geotechnical conditions, which are often characterized by significant uncertainty or variability. The model represents these conditions through the vector $\mathbf{X}$, consisting of selected geotechnical characteristics that ultimately may affect the construction time, such as rock quality and groundwater conditions. In essence, this translates to the conceptual function $Q = g[\mathbf{X}(l)]$, which serves as the mechanism through which site conditions are factored into the evaluation of construction time. Given the inherent uncertainty in the function $Q = g[\mathbf{X}(l)]$, the model treats Q as a stochastic variable.

The total time (T) and cost (C), for a tunnel excavated through more than one geotechnical zone, can be calculated as:

$$T = T_{\text{N}} + T_{\text{E}} = \sum_{u=1}^{n_{\text{zone}}} \int_{L_u} g_u[\mathbf{X}(l)]\,dl + \sum_{i=1}^{n_{\text{dis}}} T_{\text{E},i} \tag{3.1a}$$

$$C = C_{\text{N}} + C_{\text{E}} = \sum_{u=1}^{n_{\text{zone}}} \sum_{\alpha=1}^{n_\alpha} \int_{L_u} z_\alpha g_\alpha[\mathbf{X}(l)]\,dl + \sum_{i=1}^{n_{\text{dis}}} C_{\text{E},i}. \tag{3.1b}$$

where L_u represents the length of the u^{th} geotechnical zone, and z_α stands for the cost variable associated with one of the three cost categories (n_α): time-dependent, quantity-dependent, and fixed costs. The function $g_u[\mathbf{X}(l)]$ represents the production effort, which depends on the geotechnical characteristics ($\mathbf{X}$) relevant for construction time and cost in zone u. The n_{dis} stands for the number of disruptive event types, while $T_{\text{E},i}$ and $C_{\text{E},i}$ represent the time delay and incurred cost resulting from the occurrence of disruptive event type i.

3.1.2 Practical estimation of tunneling time

Normal time within a geotechnical zone

Establishing the relationship between geotechnical characteristics and production effort, $Q = g_u[\mathbf{X}(l)]$, within a specific geotechnical zone presents a considerable challenge. This complexity arises from the fact that production effort is often influenced by multiple geotechnical characteristics. Consequently, in practical applications in the original KTH model, the initial step involves identifying all relevant geotechnical characteristics (e.g., rock quality and groundwater conditions) that impact production effort. Subsequently, experts subjectively categorize the range of values of these characteristics into three classes: poor (III), fair (II), and good (I) production classes. A "good" production class implies that, in comparison to the fair or poor production classes, less construction time is required per meter of tunnel.

Considering that any problem arising from a single geotechnical characteristic can impede the entire construction process, each characteristic is considered to be a crucial "link" in a series system that constitutes the construction process. The construction process falls into Production Class I (good) when all geotechnical characteristics fall into class I, Production Class III (poor) when one or more characteristics fall into class III, and Production Class II for all other scenarios.

Isaksson and Stille [5] approximated the probabilities associated with each production class of the overall construction process (the series system) are approximated by conducting random sampling of the geotechnical characteristics. Each individual sample is viewed as a Boolean variable, having a binary value of either 0 or 1. Accordingly, the Boolean variables S_z and M_z are defined as:

$$S_z = \begin{cases} 1 & \text{If the characteristic is in production class I or II} \\ 0 & \text{If the characteristic is in production class III} \end{cases} \tag{3.2a}$$

$$M_z = \begin{cases} 1 & \text{If the characteristic is in production class I} \\ 0 & \text{If the characteristic is in production class II or III.} \end{cases} \tag{3.2b}$$

The production class of the construction process in the respective cases is represented with the variables S_s and M_s and can be estimated as:

$$S_s = S_1 S_2 ... S_n = \prod_{z=1}^{n} S_z \tag{3.3a}$$

$$M_s = M_1 M_2 ... M_n = \prod_{z=1}^{n} M_z. \tag{3.3b}$$

The proportions of the production classes of the construction process (S_t) along the tunnel can be estimated through the following equations:

$$P(S_\mathrm{t} = \mathrm{I}) = \mathrm{P(M_s = 1)} = \prod_{\mathrm{z=1}}^{\mathrm{n}} \mathrm{P_z(M_z = 1)} \tag{3.4a}$$

$$P(S_\mathrm{t} = \mathrm{III}) = \mathrm{P(S_s = 0)} = 1 - \prod_{\mathrm{z=1}}^{\mathrm{n}} [1 - \mathrm{P_z(S_z = 1)}] \tag{3.4b}$$

$$P(S_\mathrm{t} = \mathrm{II}) = 1 - \mathrm{P(S_t = I)} - \mathrm{P(S_t = III)}, \tag{3.4c}$$

where the probability $P_z(M_z = 1)$ represents the probability that the z^{th} Boolean variable, M_z, falls into production class I, while $[1 - P_z(S_z = 1)]$ indicates the probability of the z^{th} Boolean variable, S_z, being in production class III.

In the original model, Isaksson and Stille [5], [50] used triangular distributions to model the uncertainty of the production effort within each production class. Accordingly, experts subjectively assign minimum (a), most likely (b), and maximum (c) production efforts in each production class. The mean value (m_i) and standard deviation (σ_i) of the production effort in each production class are given by:

$$m_i = (a+b+c)/3 \tag{3.5}$$

$$\sigma_i = \sqrt{(a^2+b^2+c^2-ab-ac-bc)/18}, \tag{3.6}$$

where i can take the values I, II, and III, for the three production classes. Subsequently, the mean value (μ_Q^u) and standard deviation (σ_Q^u) of production effort in the u^{th} geotechnical zone can be obtained as a mixture distribution:

$$\mu_Q^u = \sum P_i m_i \tag{3.7}$$

$$\sigma_Q^u = \sqrt{\sum_i (\sigma_i^2 + d_i^2 P_i)}, \tag{3.8}$$

where P_i represents the probabilities of the production classes of the construction process, i.e. $P(S_{\mathrm{t}} = I)$, $P(S_{\mathrm{t}} = II)$, and $P(S_{\mathrm{t}} = III)$. In essence, this implies that a simplifying assumption is made that the production effort within each production class is normally distributed. The d_i can be obtained as:

$$d_i = \mu_Q^u - m_i. \tag{3.9}$$

The normal time in the u^{th} geotechnical zone, T_{N}^u, is assumed to be a normal distribution according to the Central Limit Theorem:

$$T_{\mathrm{N}}^u \to \mathcal{N}(\mu_{T,\mathrm{N}}^u, \sigma_{T,\mathrm{N}}^u), \tag{3.10}$$

with the mean value $\mu_{T,\mathrm{N}}^u$ and standard deviation $\sigma_{T,\mathrm{N}}^u$ that are obtained as:

$$\mu_{T,\mathrm{N}}^u = L_u \mu_Q^u \tag{3.11}$$

$$\sigma_{T,\mathrm{N}}^u = \sqrt{L_u}\sigma_Q^u, \tag{3.12}$$

where L_u is the tunnel length in the u^{th} geotechnical zone. With an increasing L_u, the standard deviation of the normal time ($\sigma_{T,\mathrm{N}}^u$) tends to decrease as a result of the averaging process. The standard deviation of the *average* production effort for a unit length ($\sigma_{\bar{Q}}$) is expressed as:

$$\sigma_{\bar{Q}} = \Gamma \sigma_Q, \tag{3.13}$$

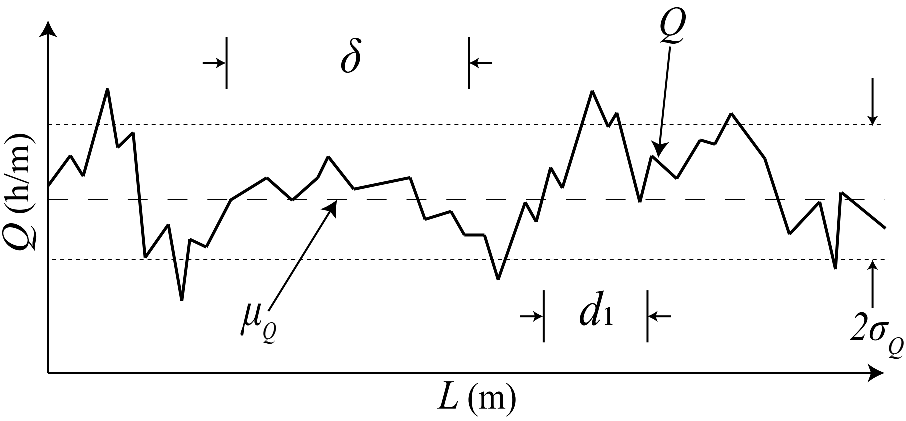

Figure 3.1. A visual representation of the production effort (Q), its point-specific standard deviation (σ_Q), the "scale of fluctuation" (δ), and the distance between "mean crossings" (d_1), all in the context of the tunnel's length (L).

where Γ is the variance reduction factor which is calculated through:

$$\Gamma \approx \sqrt{\frac{\delta}{\delta + L_u}}, \tag{3.14}$$

where δ is the scale of fluctuation which accounts for spatial correlation. Finally, the standard deviation of the normal time ($\sigma^u_{T,\mathrm{N}}$) is calculated by:

$$\sigma^u_{T,\mathrm{N}}(\delta) = L_u \Gamma \sigma^u_Q = L_u \sqrt{\frac{\delta}{\delta + L_u}} \sigma^u_Q. \tag{3.15}$$

Clearly, as δ approaches the unit length $l = 1$, we observe a trend towards the uncorrelated scenario, where $\sigma^u_{T,\mathrm{N}}(\delta = 1)$ approximates $\sqrt{L_u}\sigma^u_Q$.

Figure 3.1 provides a visual depiction of the production effort (Q), the point-specific standard deviation (σ_Q), and the "scale of fluctuation" (δ). The δ pertains to the distance over which the geotechnical characteristic demonstrates significant auto-correlation along the tunnel length (L) and can be approximated as:

$$\delta = \sqrt{\frac{2}{\pi}} d_1, \tag{3.16}$$

where d_1 is the distance between mean crossings (see Figure 3.1).

Exceptional time within a geotechnical zone

The exceptional time (T_E) is estimated based on our understanding of the probability and consequences of disruptive events. Different disruptive events happen with varying probabilities and consequences. Some disruptive events are influenced by the method's productivity, while others are not. Disruptive events can exhibit low probabilities yet result in significant consequences, such as when the actual geotechnical characteristics deviate significantly from the method's typical operating range, necessitating method changes. Conversely, some disruptive events might have high probabilities but result in minor consequences, like minor breakdowns.

In the original KTH model a classification into distinct event types has been done, encompassing [5], [50]:

- Production-dependent geological events: the probability of surpassing the limit where the method of construction works fairly, signifying production class II.
- Randomly-occurring geological events: Locally significant deviations of geological conditions.
- Randomly-occurring mechanical events: Component failure in the machinery or equipment.
- Randomly-occurring gross errors: Consequences of lack of competence.

For the first bullet point, if the probability-density function of the geotechnical characteristics (X) is denoted as $f(x)$, then the probability of the factor surpassing the critical value (x_c) can be expressed as:

$$P(X > x_\mathrm{c}) = \int_{x_\mathrm{c}}^{\infty} f(x)dx. \tag{3.17}$$

The probability of x failures, $P_x(x)$, can be obtained using the Binomial distribution:

$$P_x(x) = \binom{n}{x} p^x (1-p)^{n-x}, \tag{3.18}$$

where p is the probability of occurrence of the Production-dependent geological event and n is the total number of construction rounds. Using Monte Carlo simulation, the number of failures (represented as 'x') is randomly drawn from this distribution. Subsequently, this value is multiplied by the corresponding consequence (time delay) associated with that particular number of failures.

For the second bullet point, the random variable X represents the count of geological disruptive events that occur randomly along a tunnel of length L. The probability of exactly x disruptive events occurring within the tunnel length L is modelled using Poisson distribution:

$$P(x) = \frac{(\lambda L)^x e^{-\lambda L}}{x!}, \tag{3.19}$$

where λ is the number of randomly-occuring geological disruptive events per unit length of tunnel.

For the third bullet point, this estimation is related to the failure rate of machine components. The probability of system failure over the time period (0, t) is calculated as:

$$P_s(\text{failure}) = 1 - \exp(-\sum_{\mathrm{j=1}}^{\mathrm{n}} \lambda_\mathrm{j}\mathrm{t}), \tag{3.20}$$

where λ_j i the failure rate of the j^{th} component.

For the fourth bullet point, the analysis methods employed for human factors cannot be directly applied in the same manner as those used for technical components. Various approaches for estimating the probability and consequences associated with human errors encompass:

- The Technique for Human Error Rate Prediction (THERP)
- The Success Likelihood Index Method (SLIM)
- The Prediction of Operator Failure rate (PROF)
- Action Error Analysis (AEA)

The application of these methods to estimate the probability and consequences of human errors is relatively limited. Consequently, the outcomes derived from these methods are best suited for providing a rough estimate rather than precise calculations. Nonetheless, these methods offer a means of addressing the influence of human factors on the tunneling process.

3.2 Updated KTH model

This section provides a condensed summary of all the updates and improvements made to the KTH model across various papers. It serves as an overview of the entire development process, offering a clear and unified description of the model's updates. Essentially, it captures the key enhancements and modifications implemented, providing readers with a comprehensive understanding of the updated KTH model and its advancements.

3.2.1 The risk model

A thorough examination of the literature pertaining to probabilistic time and cost estimation in tunneling projects has been carried out (see Section 1.3). The aim was to gain insights into possible enhancements in model accuracy. As a result of this literature review, a risk model was developed that serves as a framework for a subsequent discussion on the practical application of the existing time and cost estimation models [11], [12]

Within the risk model, six principal risk domains, each encompassing specific hazards (defined as vulnerabilities that carry the potential for damage), were identified. These risk domains have a discernible impact on the time and cost considerations of tunneling projects:

$$T = f(\text{geology}, \text{design}, \text{contract}, \text{competence}, \text{machinery}, \text{economy}) \tag{3.21a}$$

$$C = h(\text{geology}, \text{design}, \text{contract}, \text{competence}, \text{machinery}, \text{economy}). \tag{3.21b}$$

The risk model, as depicted in Figure 3.2, is elaborated upon by Mohammadi et al. [11]. It examines how estimation models take into account three primary sources of uncertainty: geology (including geotechnical conditions), construction performance variability, and disruptive events. Mohammadi et al. [11] goes beyond discussing the risk model; it also explores the end-users of the estimation models, whether they are the client or the contractor. Furthermore, Mohammadi and Spross [12] explore the elements influencing the precision of subjective estimations during the pre-operational project phases within the framework of the risk model, offering suggestions for possible improvements in estimation accuracy.

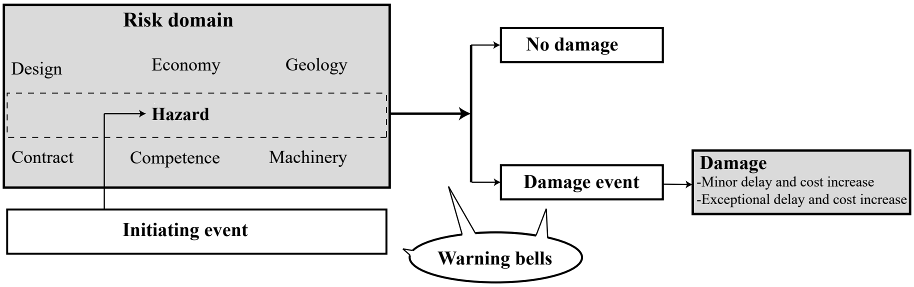

Figure 3.2. The risk model for illustrating the hazards associated with time and cost estimation in tunneling projects [12].

3.2.2 Calculation of normal time

Practical application of the KTH model

The first modification of the KTH model involves integrating a work breakdown structure (WBS) instead of the production classes approach. This change aims to facilitate more tangible subjective assessments and provide a more detailed representation of the construction process. Consequently, construction classes are defined as a combination of required production activities (such as pre-excavation grouting, excavation sequence, and concrete lining) as prescribed in the work breakdown structure (WBS). Various combinations of the required production activities along the tunnel route (the construction class to be used) depend mainly on the geological conditions. These production activities are then further dissected into their unit activities. This approach enables experts to evaluate the input distributions in relation to the time required for each unit activity, eliminating the need to assess the combined time for production classes, which is a more abstract concept.

An approach is also introduced to represent the uncertainty related to the length of shorter and recurring geotechnical zones using a Poisson distribution. Additionally, the assessment of T_{E} now involves treating the delay time caused by disruptive events as a stochastic variable. In addition, numerical simulation is employed to sum the stochastic variables of unit activity times. In contrast, the original version of the model relies on a more cumbersome and less precise analytical approach (Section 3.1.2). The utilization of the updated model for estimating the time required for the Uri headrace tunnel project is detailed in Mohammadi et al. [13]. Furthermore, the implementation of the PERT distribution for representing the duration of unit activities is showcased in Mohammadi and Spross [15], including a comparative analysis with scenarios employing triangular distributions to account for the uncertainty in unit activities' duration.

Typical performance variability of construction time

In the updated model, the three key components affecting construction performance variability are identified as:

- typical performance variability: variability due to performance pace of production crew
- minor machinery delays: delays in the order of a few hours that are caused by machinery breakdown

- minor performance delays: delays in the order of a few hours that are caused by occasional poor performance of production crew.

The details and underlying analyses are presented in Mohammadi et al. [16]. In the typical scenario, the production effort of the a^{th} production activity in its k^{th} class, related to typical performance variability, is denoted as $Q'_{a,k}$ and can be determined as:

$$Q'_{a,k} = \sum_{j=1}^{n_q^a} q'_{j,a}, \tag{3.22}$$

where n_q^a represents the number of unit activities in the a^{th} production activity, and $q'_{j,a}$ denotes the production effort associated with the typical performance variability of the j^{th} unit activity, which can be effectively modeled using triangular distributions. The production effort of the a^{th} production activity (Q'_a) is derived as a mixture distribution, combining the production efforts in all k classes ($Q'_{a,k}$) weighted by their assessed proportions ($p_{a,k}$) along the tunnel length:

$$Q'_a = \sum_{k=1}^{n_k} p_{a,k} Q'_{a,k}. \tag{3.23}$$

Here, n_k denotes the number of classes for the relevant geotechnical characteristic. The production effort (Q') can be subsequently calculated as:

$$Q' = \sum_{a=1}^{n_a} Q'_a, \tag{3.24}$$

in this context, n_a refers to the number of production activities. The portion of normal time associated with typical performance variability of production effort (T'_{N}) can be computed as:

$$T'_{\mathrm{N}} \to \mathcal{N}\left(\mu'_{T,\mathrm{N}}, \sigma'_{T,\mathrm{N}}\right), \tag{3.25}$$

where the mean ($\mu'_{T,\mathrm{N}}$) and standard deviation ($\sigma'_{T,\mathrm{N}}$) of T'_{N} are obtained as:

$$\mu'_{T,\mathrm{N}} = L\mu_{Q'}, \tag{3.26}$$

$$\sigma'_{T,\mathrm{N}} = L\sqrt{\frac{\delta}{\delta + L}}\sigma_{Q'}. \tag{3.27}$$

Minor machinery delays

The minor machinery delay ($\kappa_{\mathrm{m},i}$) during the i^{th} round of the a^{th} production activity can be represented by an exponential distribution:

$$\kappa_{\mathrm{m},i} = (\lambda_{\mathrm{m}}^a) e^{(-\lambda_{\mathrm{m}}^a n_{\mathrm{r}}^a)}, \tag{3.28}$$

where λ_{m}^a denotes the rate of minor machinery delay occurrences during the unit activities of the a^{th} production activity, and n_{r}^a is the total number of construction rounds in the a^{th}

production activity. The minor machinery delays for the a^{th} production activity ($\kappa_{\text{m,a}}$) can be derived using the following equation:

$$\kappa_{\text{m},a} = \sum_{i=1}^{n_{\text{r}}^{a}} \kappa_{\text{m},i}, \tag{3.29}$$

Finally, the cumulative minor machinery delays (κ_{m}) can be computed as:

$$\kappa_{\text{m}} = \sum_{a=1}^{n_a} \kappa_{\text{m},a}, \tag{3.30}$$

where n_a is the number of production activities. It is important to note that κ_{m} is expressed in units of time.

Minor performance delays

The minor performance delay ($\kappa_{\text{p},i}$) occurring during the i^{th} construction round of the a^{th} production activity can be modeled using an exponential distribution:

$$\kappa_{\text{p},i} = (\lambda_{\text{p}}^{a}) e^{(-\lambda_{\text{p}}^{a} n_{\text{r}}^{a})}, \tag{3.31}$$

where λ_{p}^{a} represents the rate of minor performance delay occurrence during the unit activities of the a^{th} production activity, and n_{r}^{a} stands for the total number of rounds of the a^{th} production activity. The minor performance delays for the a^{th} production activity ($\kappa_{\text{p,a}}$) can be determined using:

$$\kappa_{\text{p},a} = \sum_{i=1}^{n_{\text{r}}^{a}} \kappa_{\text{p},i}, \tag{3.32}$$

The total minor performance delays (κ_{p}) can be determined:

$$\kappa_{\text{p}} = \sum_{a=1}^{n_a} \kappa_{\text{p},a}, \tag{3.33}$$

where the variable n_a represents the number of production activities. Note that κ_{p} is also expressed in units of time.

Normal time

Finally, the normal time (T_{N}) can be calculated as:

$$T_{\text{N}} = T_{\text{N}}^{'} + \kappa_{\text{m}} + \kappa_{\text{p}}. \tag{3.34}$$

Mohammadi et al. [16] provides an application example for time estimation, focusing on Adit 4 of the Uri hydro-power project.

3.2.3 Time estimation of tunnels with multiple headings

This proposed update involves the utilization of a step-wise procedure to explicitly model the total time for each construction round, T_l. The T_l encompasses both normal time ($T_{\text{N},1}$) and exceptional time ($T_{\text{E},1}$) of construction rounds. Adopting this round-by-round modeling approach provides three contributions:

- introducing an alternative approach for calculation of tunneling time
- facilitating the time estimation process for shorter tunnels (which was not viable in the previous updates in Section 3.2)
- enabling the model to account for time estimation of network underground structures with multiple headings

Let us assume that the construction of a tunnel with a total length of L necessitates a series of m construction rounds, each having a length of l_r. The vector representing the normal time for these construction rounds $\mathbf{T}_{\text{N},r}$ can be calculated as:

$$\mathbf{T}_{\text{N,r}} = l_\text{r}.\mathbf{Q}, \tag{3.35}$$

where $\mathbf{Q} = [Q_1, Q_l, ..., Q_m]$, with Q_l representing identical stochastic variables (Equations 3.22—3.24). The normal time of the l^th construction round, $T_{\text{N},l}$, can be expressed as $T_{\text{N},l} = l_\text{r} Q_l$.

Under the assumption that disruptive events in consecutive construction rounds are independent, with a maximum of one event of each type occurring during each round, the exceptional time of the i^th event type for a single round, denoted as $T_{\text{E},i,l}$, follows a Bernoulli process with a probability of occurrence of p_i:

$$T_{\text{E},i,l} = \begin{cases} 0 & \text{If disruptive event does not occur} \\ \kappa_i & \text{If disruptive event occurs,} \end{cases} \tag{3.36}$$

where κ_i is a random variable denoting the delay time resulting from the disruptive event during the l^th construction round. The particular disruptive event type, and thus the values of p_i and κ_i, are dependent on the ground conditions at the location of the l^th construction round.

To consider the spatial correlation among the elements of $\mathbf{Q}$, the Markov Chain Monte Carlo method with the Metropolis–Hastings (MH) algorithm is employed [51]. Comprehensive details of this method can be found in various texts like [52] and [53]. This approach involves dependent sampling from a selected proposal probability density function $f_\text{p}(Q)$ that closely approximates the target PDF $f_\text{t}(Q)$. To enable a round-by-round simulation of construction time, the MH algorithm is integrated with the Bernoulli process that models the occurrence of disruptive events. For a single tunnel constructed from one front, this gives the following algorithm [14]:

1. Set the elapsed normal and exceptional times to their start values $T_\text{N} = 0$ and $T_\text{E} = 0$.
2. Sample Q_1 from the proposal PDF $f_\text{p}(Q)$ and calculate the normal time $T_{\text{N},1}$ and exceptional time $T_{\text{E},1}$ for the first excavation round, using Eqs. 3.35 and 3.36, add them to the elapsed times $T_\text{N} = T_{\text{N},1}$ and $T_\text{E} = T_{\text{E},1}$, and record the constructed length $L_\text{con} = l_r$.

```
3. for excavation rounds $l = 2$ to $m$ do
    (a) Generate a sample $u$ of $U$, which is uniformly distributed in the range [0,1], and a candidate $Q_{\mathrm{can}}$ from the proposal PDF $f_{\mathrm{p}}(\cdot \mid Q_{l-1})$
    (b) Calculate the acceptance rate as $r = \frac{f_{\mathrm{p}}(Q_{l-1}|Q_{\mathrm{can}}) f_{\mathrm{t}}(Q_{\mathrm{can}})}{f_{\mathrm{p}}(Q_{\mathrm{can}}|Q_{l-1}) f_{\mathrm{t}}(Q_{l-1})}$
    (c) Set
        $Q_l = \begin{cases} Q_{\mathrm{can}} & \text{if } u < r \\ Q_{l-1} & \text{otherwise} \end{cases}$
    (d) Calculate the normal time of the construction round for this sample as $T_{\mathrm{N},l} = l_{\mathrm{r}} Q_l$
    (e) Update the normal time as $T_{\mathrm{N}} = T_{\mathrm{N}} + T_{\mathrm{N},l}$
    (f) for each exceptional event type $i = 1$ to $n_{\mathrm{d}}$ do
        • Generate a sample $v_i$ of $V$, which is uniformly distributed in the range [0,1], and obtain the exceptional time for each event type ($\kappa_i$) if $v_i < p_i$
        • Calculate the exceptional time of this round as: $T_{\mathrm{E},l} = \sum_{i=1}^{n_{\mathrm{d}}} \kappa_i$
    end
    (g) Update the overall exceptional time as: $T_{\mathrm{E}} = T_{\mathrm{E}} + T_{\mathrm{E},l}$
    (h) Calculate the total time of this round as: $T_l = T_{\mathrm{N},l} + T_{\mathrm{E},l}$
    (i) Update the constructed length: $L_{\mathrm{con}} = L_{\mathrm{con}} + l_r$
end
4. Return the vector of times of construction rounds $\mathbf{T} = [T_1, T_l, ..., T_m]$
5. Calculate the total time as $T = \sum_{l=1}^{m} T_l$
```

The target PDF, $f_{\mathrm{t}}(Q)$, refers to the PDF of Q while the proposal PDF, $f_{\mathrm{p}}(Q)$, is a known distribution that closely approximates the Q. The acceptance rate, akin to the *scale of fluctuation* (δ) utilized in the original version of the KTH model (refer to [5] and [54]), addresses spatial correlation. Different values of r can be utilized to accommodate a range of geological contexts (see also [14]).

In a scenario involving the construction of a tunnel using two converging fronts, the following algorithm enables the computation of the total time, accounting for uncertainties related to the meeting points of these fronts [14]:

1. Using the algorithm for a single tunnel, generate a vector $\mathbf{T} = [T_1, T_2, \ldots, T_m]$, where each element represents the total time for each construction round along the whole tunnel.

2. Let T_{D} and T_{U} be the elapsed construction time for the downstream and upstream faces (the two ends of the tunnel), and let L_{D} and L_{U} be the corresponding constructed lengths from the respective starting points.

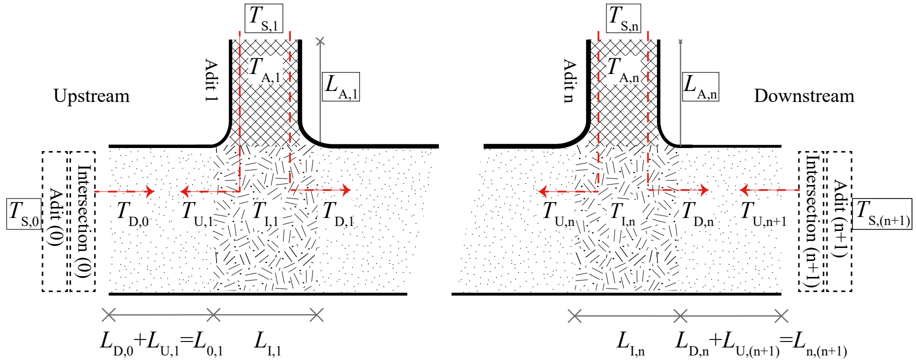

Figure 3.3. An illustration of a tunnel featuring multiple excavation faces. The indices U, D, A, I, and S denote upstream, downstream, adit, intersection, and starting time respectively. The numbers 0 to $n+1$ in the index indicate the access adit. L and T represent the length and construction time respectively. The dashed arrows depict the headings. Adits 0 and $n+1$, along with Intersections 0 and $n+1$, are dummy components included to facilitate smoother formulations. Their length and construction time are both set to zero.

3. Set $T_{\mathrm{D}} = T_1$ and $T_{\mathrm{U}} = T_m$, and let T_{D} increase by adding times with ascending subscripts in $\mathbf{T}$, and let T_{U} increase by adding time with descending subscripts, according to the following:

   repeat Compare the current elapsed times T_{D} and T_{U}:

   - **if** the difference in elapsed time is larger than the time to construct the next round on the face with the shortest elapsed time
   - **then** add only the time of that next round to the elapsed time of the quicker face
   - **else** add the times of the respective next rounds to both

   until $L_{\mathrm{D}} + L_{\mathrm{U}}$ is equal to the total length of the tunnel

4. **return** L_{D}, L_{U}, T_{D}, and T_{U}. (L_{D} and L_{U} represent the distances to the meeting point (from the relevant tunnel portal) and T_{D} and T_{U} represent the construction time to get there

In scenarios involving tunnels with multiple construction paths with n access adits (see Figure 3.3) all segments of the main tunnel between adits have construction times denoted as $T_{\mathrm{D},i}$ $(i = 0, ..., n)$ and $T_{\mathrm{U},i}$ $(i = 1, ..., n+1)$, where the subscripts D and U refer to the two ends of the tunnel. These sections constitute tunnels featuring two converging fronts: $T_{\mathrm{D},i}$ and $T_{\mathrm{U},i+1}$ $(i = 0, ..., n)$. The vectors representing the total time of construction rounds for these sections, denoted as $\mathbf{T}_{i,i+1} = [T_{1(i)}, ..., T_{m(i)}]$ $(i = 0, ..., n)$, can be derived using the algorithm designed for a single tunnel, with the fixed lengths of each section as:

$$L_{i,i+1} = L_{\mathrm{D},i} + L_{\mathrm{U},i+1} \quad i = 0, ..., n, \tag{3.37}$$

Additionally, the total number of construction rounds for each section is denoted $m(i)$ and determined as:

$$m(i) = \lceil \frac{L_{i,i+1}}{l_{\mathrm{r}}} \rceil. \tag{3.38}$$

Here, l_{r} represents the length of construction rounds and the notation $\lceil\ \rceil$ denotes the ceiling function, signifying that any fractional value enclosed within it is rounded up to the nearest integer, because the number of construction rounds must be an integer. The algorithm designed for a tunnel with two converging fronts can be applied to determine the total time required for the sections of the main tunnel in between adits. Considering the distinct starting times of the converging fronts, two additional elements need inclusion in $\mathbf{T}_{i,i+1}$: one at the start, $T_{0(i)}$, and another at the end, $T_{m(i)+1}$:

$$T_{0(i)} = T_{\mathrm{S},i} + T_{\mathrm{A},i} + T_{\mathrm{I},i} \quad i = 0, \ldots, n \tag{3.39a}$$

$$T_{m(i)+1} = T_{\mathrm{S},i} + T_{\mathrm{A},i} + T_{\mathrm{I},i} \quad i = 1, \ldots, n+1, \tag{3.39b}$$

Here, $T_{\mathrm{A},i}$ and $T_{\mathrm{I},i}$ represent the total construction times of the i^{th} adits and intersections, respectively. These can be computed using the algorithm designed for a single tunnel. Meanwhile, $T_{\mathrm{S},i}$ denotes the starting time of the i^{th} adit, which constitutes a stochastic variable. Modelling the uncertainty in starting time can be achieved by assigning statistical distributions such as the triangular distribution. Different distributions for Q might be necessary to accommodate differing tunnel geometries across various sections, such as adits, intersections, and the main tunnel. These distributions can be tailored to suit the specific characteristics of each section, ensuring an accurate representation of the construction process.

The $T_{\mathrm{D},i}$ $(i = 0, \ldots, n)$ denote the total construction time for construction paths $\mathrm{C}_{i,\mathrm{D}}$. The construction paths $\mathrm{C}_{i,\mathrm{D}}$ have the length consisting of adit i, intersection i, and the part of the main tunnel constructed through adit i towards the tunnel end that is denoted by D. The $T_{\mathrm{U},i}$ $(i = 1, \ldots, n+1)$ represents the total time for construction paths $\mathrm{C}_{i,\mathrm{U}}$. Ultimately, the total project time (T) corresponds to the construction path with the longest duration:

$$T = \max[T_{\mathrm{D},0}, \ldots, T_{\mathrm{D},n}, T_{\mathrm{U},1}, \ldots, T_{\mathrm{U},(n+1)}]. \tag{3.40}$$

As a result, the critical path of the project is not predetermined; it can vary based on the ground conditions and construction progress along each path. Employing Monte Carlo simulation enables the consideration of variations in the total time across all construction paths and the project as a whole.

3.3 Additional theoretical and practical details

Additional details on the theory and the practical application of the updated KTH model and the risk model can be found in the scientific articles that were produced in this research project. Six articles were written, denoted Papers A-F in the PhD thesis version of this report.

Paper A - Mohammadi et al. [11]

> Mohammad, M., Spross, J., Stille, H. (2024). Models to analyze risk in time and cost estimation of tunneling projects, *Geotechnical and Geological Engineering, 42*, 1445-1457. DOI: https://doi.org/10.1007/s10706-023-02627-x

Paper B - Mohammadi et al. [13]

Mohammad, M., Spross, J., Stille, H. (2023). Probabilistic time estimation of tunneling projects: the Uri headrace tunnel, *Rock Mechanics and Rock Engineering, 56 (1)*, 703-717. DOI: https://doi.org/10.1007/s00603-022-03022-3

Paper C - Mohammadi and Spross [15]

Mohammadi, M., Spross, J. (2023). Modeling uncertainty of activity duration in probabilistic time estimation of tunneling projects. In: *Proceedings of the 15th ISRM Congress 2023 & 72nd Geomechanics Colloquium*, 403-408, Salzburg, Austria. Link: OnePetro.org

Paper D - Mohammadi et al. [16]

Mohammadi, M., Vandyousefi, H., Askari, M., Spross, J. Modelling construction performance variability for probabilistic time estimation of tunneling projects. Submitted to *Georisk*. Manuscript available in the printed PhD thesis.

Paper E - Mohammadi et al. [14]

Mohammad, M., Spross, J. Probabilistic time estimation of underground structures constructed with multiple headings. Submitted to *Tunnelling and Underground Space Technology*. Manuscript available in the printed PhD thesis.

Paper F - Mohammadi and Spross [12]

Mohammadi, M., Spross, J. (2023). Risk model for understanding uncertainty in time and cost estimation in tunneling phases. In: *Proceedings of the 15th International Conference: Underground Construction Prague 2023*, Prague, Czech Republic.

4. DISCUSSION

In this chapter, several significant aspects related to the updated KTH model are addressed. Section 4.1 emphasizes the advantages introduced by the updated KTH model. Section 4.2 covers a broader topic, focusing on the distinctions between the KTH model and other existing models. Section 4.3 provides an explanation of the novel approach to modeling geological uncertainties in the KTH model, setting it apart from other models. Lastly, Section 4.4 elaborates on how decision-makers can make use of the KTH model.

4.1 The advantages of updated KTH model

The enhanced model's application process offers several distinct advantages:

- It allows for obtaining the distribution of production efforts across all production activities (Section 3.2.2), a capability absent in the original version. This illuminates the individual impacts of each production activity, thus providing contractors with valuable insights into optimizing construction work based on the effects of diverse geotechnical characteristics on normal time.

- By introducing the production efforts of individual activities and their unit activities, the model simplifies the assessment of production efforts for experts. Unlike the original model, experts no longer need to consider the unit activities of multiple production activities jointly (Section 3.2.2), making their subjective assessments more manageable and concrete.

- The calculation method for exceptional time (T_E) becomes more transparent and informative (Section 3.2.3), offering insights into T_E distribution. This enhanced process makes T_E easier to comprehend while yielding additional information about its distribution.

- The model's development enables distinct consideration of uncertainties related to minor machinery delays and minor performance delays (Section 3.2.3). This refined approach enhances the modeling of construction performance variability, offering a more detailed perspective. Furthermore, this update empowers contractors to factor in the influences of machinery and personnel both before and during the construction process.

4.2 The differences between the KTH model and other models

The main differences between the KTH model and other models (the DAT [4] and Špačková's model [55]) are as follows:

- The DAT and Špačková's model utilize a Markov Chain Monte Carlo (MCMC) technique to generate geological profiles along the tunnel route, allowing the lengths of geotechnical zones to be treated as stochastic variables. This method, drawing upon data from tunnel route investigations like borehole data, offers versatility in addressing a wide range of variability in the geological setting, making it applicable across numerous projects. In contrast, the updated KTH model approaches this uncertainty and variability differently. Users initially define the project's geological setting and then select the method for modeling the uncertainty. This approach provides flexibility, enabling the use of various statistical methods and approaches tailored to the specific conditions at the project site. For instance, in the Uri headrace tunnel case study presented by Mohammadi et al. [13], a Poisson distribution is employed to model fault occurrences, illustrating a specific site condition. The updated model's adaptability allows for flexibility in modeling geological uncertainty, accommodating diverse methods depending on specific site conditions, thereby enhancing its applicability across varied projects.

- In the DAT and Špačková's model, ground class profiles specify the probabilities of occurrence for all ground classes at any location along the tunnel route. These profiles are then employed in the construction simulation module to compute tunneling time. In contrast, the updated KTH model adopts a different approach, utilizing the proportion of each ground class with respect to the total tunnel length as the probability of its occurrence. This method allows modeling geological uncertainty without necessitating the construction of specific ground class profiles.

- In the DAT and Špačková's model, advance rates are linked to construction classes via user-defined equations for tunneling time calculations, which reflect subjective expert assessments. However, the updated KTH model diverges in methodology: it utilizes the inverse of the advance rate, termed as production effort (Q), to compute tunneling time. Although the subjective assessment of advance rate and production effort remains similar, this alteration changes the calculation process for normal time (T_{E}). By basing calculations on production effort, the model enables the derivation of distributions for various production effort components. This detailed breakdown offers valuable insights into the individual impacts of production activities and geotechnical characteristics on T_{E}.

4.3 Geological uncertainties in the KTH model

By leveraging production effort (Q) for tunneling time computation, the updated KTH model brings a distinctive capability to the literature, i.e. the utilization of the Metropolis-Hastings (MH) algorithm within the framework of Markov Chain Monte Carlo simulation for modelling uncertainties about the geology along the tunnel route. Employing the MH algorithm to regenerate the distribution of Q allows for modeling geological variations along the tunnel route. This approach not only adds diversity to the field's methods for modeling geological uncertainties but also proves beneficial in scenarios where limited information about the geological conditions along the tunnel route are available. For instance, in projects like Uri, where a general understanding of the overall geological setting is available but detailed data might be lacking, this method remains advantageous. Furthermore, employing the MH algorithm enables a round-by-round simulation of the tunneling process using the KTH model. This capability unveils two advantageous aspects:

- Previously, the model was suited only for tunnels where the tunnel length significantly exceeded the scale of fluctuation, δ. However, the updated version extends its applicability, now enabling time estimation for shorter tunnels as well.

- In tunnels constructed with multiple headings, accounting for uncertainty in the project's critical path becomes feasible through round-by-round simulation.

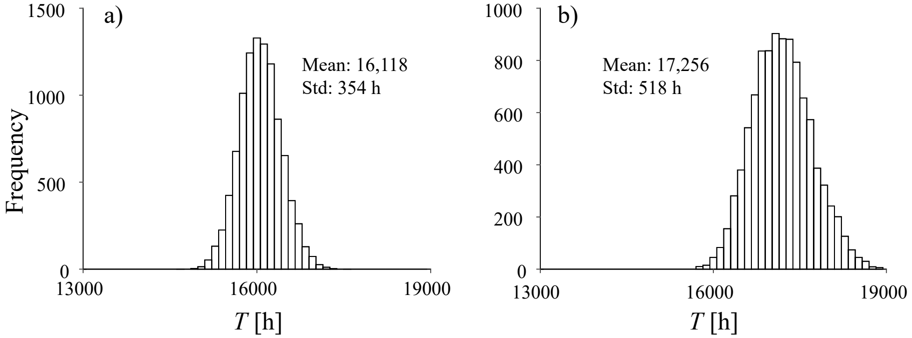

Figure 4.1. a) The total construction time of the Uri headrace tunnel obtained using the updated KTH model with uncertain critical path b) The total time of the Uri headrace tunnel obtained using a pre-determined critical path [14]

In the case of tunnels constructed through multiple headings, the prevailing approach in literature simplifies time estimation by assuming the longest section as the project's critical path. However, in practical scenarios, this oversimplified method can lead to misleading estimations. Given the varying construction paces and the influence of disruptive events across sections, any section might potentially become the critical path during construction. Therefore, until construction completion, uncertainty prevails regarding the project's critical path. The updated model, as highlighted by Mohammadi et al. [14], addresses this uncertainty. For instance, in the Uri headrace tunnel, Mohammadi et al. [14] demonstrates the use of the updated KTH model to calculate the total time considering the uncertain critical path. Figure 4.1 illustrates the comparison between this approach and the traditional method that assumes a predetermined critical path.

The findings demonstrate that considering an uncertain critical path yields a smaller mean value and standard deviation for the total tunneling time compared to the traditional method of assuming a predetermined critical path. This discrepancy arises from accounting for critical path uncertainty, compensating for any delays in one face due to slow construction or disruptive events by the progress of the other converging face, a factor overlooked when assuming a predetermined critical path. Notably, while uncertainty in the critical path is a well-recognized aspect in building construction projects (see for instance [56]), the tunneling industry has historically overlooked this aspect. The work in Mohammadi et al. [14] stands as an effort in addressing uncertainty in the critical path for complex tunneling projects, marking a valuable contribution to the field.

4.4 Decision-makers' use of the models

A decision maker's use of a probabilistic time and cost estimation tool typically revolves around four fundamental aspects:

1. Formulating a probabilistic geological model that outlines estimated probabilities associated with encountering various geological features and disruptive events throughout the tunnel route.

2. Applying a time and cost model that furnishes the overall time and cost estimations for excavating a tunnel considering potential geological features.

3. Adapting the model to account for the client's or contractor's respective risk ownership, as delineated in the contract terms. For instance, a contractor's analysis during bid preparation might exclude considerations for conditions or events compensated additionally by the client as per the contract.
4. Utilizing the tool for budget estimation or streamlining scheduling processes to optimize project timelines and financial planning.

The utility of time and cost estimation models extends to various contexts, where different models may prove more effective based on specific purposes. Beyond solely assessing total time and cost, stakeholders like contractors or clients may seek to independently analyze the impact of diverse uncertainties on their risk exposure in a project. This includes referencing Geotechnical Baseline Reports (GBRs) to delineate cost responsibilities in adverse ground conditions. Notably, the application of probabilistic time and cost estimation models for this targeted risk management purpose remains unexplored in existing literature. While this research does not explicitly cover the model's integration with GBRs, it underscores the importance of researchers exploring multiple modeling approaches concurrently. This approach acknowledges the diverse needs of future tunnel engineers, highlighting the significance of addressing varied risk management aspects within tunneling projects.

5. CONCLUSIONS

The conclusions drawn from the literature analysis and the updated framework (the KTH model), based on the research objectives outlined in Section 1.2, are as follows:

- The literature analysis demonstrates that utilizing probabilistic approaches for estimating time and cost in transport infrastructure projects offers a more suitable method than deterministic methods, resulting in a probabilistic distribution of time and cost estimates, contrasting with the single values of the actual project outcomes. Adopting probabilistic estimation provides a more realistic perspective, making the traditional concept of cost overrun less relevant. This suggests that greater emphasis should be placed on comprehending and incorporating uncertainties into the estimation process for a project.

The enhancements and updates in the KTH model pertaining to construction performance can be summarized through three main points:

- The construction process is modelled using the work breakdown structure (WBS). Construction classes are delineated based on primary production activities, each accompanied by its specific unit activities. The selection of the construction class along the tunnel route primarily hinges on the geological condition at that specific point. This enhancement facilitates a more authentic representation of the construction process, rendering it more tangible for experts engaged in conducting subjective assessments.
- PERT distributions are utilized to represent the uncertainty in the duration of unit activities, a departure from the more commonly employed triangular distributions.
- The identification of three components—typical performance variability, minor performance delays, and minor machinery delays—contributes to the understanding of variability in construction performance. These components have been integrated into the KTH model, resulting in its enhanced capacity to address construction performance variability.

To address geological uncertainties along the tunnel route, a novel approach introduced in this thesis involving the use of Metropolis–Hastings (MH) algorithm within the framework of Markov Chain Monte Carlo (MCMC) simulation. This methodology has been incorporated into the KTH model, contributing two main enhancements:

- Enabling round-by-round simulation of tunneling construction
- Enabling the model to consider uncertainty in the critical path for tunneling projects involving multiple headings.

Finally, disruptive events are currently represented as stochastic variables, marking an enhancement over the initial version of the KTH model.

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