Mitigation Controller: A Multi-Criteria Optimization & Simulations Approach to Keep Construction Projects on Budget.

Final Report

Ali Hassan Khalife **2/14/22** **CME Master Thesis**

Mitigation Controller: A Multi-Criteria Optimization & Simulations Approach to Keep Construction Projects Within Budget

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Preface

Writing this thesis means that I am edging closer towards the end of a 30-month journey at Delft University of Technology and an end to my time at the Netherlands, a place I could easily refer to as home. Embarking on this journey will undoubtedly go down as one of the best experiences I ever had. Despite the unprecedented times the world went through for the bigger proportion of my time at the TU, I managed with the help of all the people mentioned below to go through this crisis and grow personally and professionally.

I would first like to express my utmost appreciation towards my graduation committee from the TU: Prof.dr.ir Rogier Wolfert, Dr.ir. Ruud Binnekamp, Dr. Omar Kammouh. Your continuous engagement and interest in my thesis as well as your continuous support was unmatched and educated me way beyond the horizons of a Master Thesis. No matter where I land in life, I'll always carry with me the open dialogues we held. In addition, I'll never forget the seemingly endless sessions I took part of to draw out better ideas and further developments to arrive to the great work and results we have laid out to us today. For the above and the limitless guidance, I received: Thank you!

I would also like to thank Drees&Sommer for supporting me and housing me as a graduate intern. Your belief in my ideas and potential as well as your continuous support and cooperation pushed me forward and aided me to go above and beyond. Special thanks to my external supervisor: Johan Knook as well as Frank Wetsteijn for his support in the early phases of the internship and Pim Prins for his collaboration in attaining the needed data to run the verify and validate the tool.

Reflecting on a personal level, I wouldn't have made it to this point without the support of my social circle and the friends I picked up on the way, it was a pleasure meeting each one of you and the memories we shared shall never fade. Special thanks to my CME family and in specific to my CME DISPUUT family. In Delft, I also crossed paths with two friends whom I can now proudly call brothers. To Chris and Karim, thank you for always being there for me and I'll be forever thankful for listening and speaking some sense into my mind whenever I needed it.

To my siblings Karim and Nour, much appreciation goes towards your care and affection as well as your help in pushing me forward towards achieving my goals.

Last but not least, the utmost appreciation goes to the two warriors who were also battling another unprecedented crisis back home in Beirut. Despite all the circumstances back there, not a day passed where I felt you weren't there for me. To Hassan & Lina, I owe you my life, development, and success. Not in a million years I would be the man I am today without your love and support. I hope I made you proud parents.

Unfortunately, some beloved ones didn't make it to this day, but I know they'll be watching from a better place, so much love to you and thank you for your contribution to shaping up my personality.

By the way, I hope you all enjoy reading about mitigating costs of a project **- AK**

Thesis Summary

The construction and infrastructure industry has witnessed an increase in the need for an optimized mitigation strategy to combat schedule and cost overruns amid the rise in market competitiveness and more strict timelines and budgets. Moreover, projects nowadays are more complex in terms their scope and requirements which ultimately drives more innovative and efficient solutions to enhance project risk mitigation. Typically, Monte Carlo (MC) simulations with different combinations of mitigation measures are performed until a random set of measures is chosen to satisfy the targeted budget. The main flaw of such a method is it doesn't reflect the goal-oriented control behaviour of the project manager who would only opt to the optimal mitigation strategy given a risk event and cost overrun, that is, the actual scenario (Kammouh et al., 2021). Accordingly, the Mitigation Controller (MitC) tool was developed to tackle the gap in the optimization of the selected mitigation measures. However, the aforementioned tool solely addresses the selection of mitigation measures in the case of project delays affecting a strict delivery date. The key within this project is to develop additional features to MitC and extend its usefulness into optimizing the selection of mitigation measures over the project's budget rather than its duration. With such an additional consideration, the updated version of Mitigation Controller could represent a complement to MitC and ultimately managers would apply their mitigations based on the multi-criteria-imposed constraints. Furthermore, constraints whether time or cost can change throughout the project lifecycle, thus having such a feature would enable managers to view the recommended measures from two angles: over strict timelines or budgets. The usefulness of the Mitigation Cost controller is demonstrated using a real case of a construction project in the Netherlands with the analysis performed on the go, yielding significant savings in terms of the arising negative impacts relative to current approaches used to maintain the project's budget.

Table of Contents

List of Figures

List of Tables

Chapter 1: Development Approach

Background

The construction industry is the main contributor to the world's GDP (13%) and has historically, in outside crisis times, underperformed (McKinsey & Company, 2020).The COVID-19 pandemic aftermath coupled with a series of additional sustainability requirements and resources constraints, whether time or money, will even place additional pressure on companies to outperform expectations. That being said, the room for error is minimal in such a competitive market.

Ideally, projects should be delivered within budget and on time, yet that is rarely the case. Whether it was unforeseen risks, foreseen risks with bigger impact than anticipated or construction schedule changes, the probability of completing the project within the needed budget and schedule requirements is adversely impacted (Kammouh et al., 2021). Currently, practitioners follow a series of probabilistic simulations to specify the total cost with a certain probability of success. However, the classical approach mentioned above fails in the inclusion of the human behaviour of working backwords from a specified budget and selecting the most optimal mitigation measures to attain the desired costs with the least possible negative impacts Motivated by the reasons above, the Mitigation Controller tool was developed to optimize the selection of an efficient risk mitigation strategy for projects.

The main objective of such a tool is to introduce a new mathematical constraint to only select the most efficient mitigation measures, but also to shed light on a new mindset of working backwards from the target cost. Therefore, it can be considered as a two-fold benefit: one practical with its intended use and another is a shift in mentality of managers to anticipate risk and work on mitigating its effects by a goal-oriented behaviour.

Some key takeaways of the tool and study at hand is that it stems from the development of the MitC which has been only applied on a project after its completion. Although, the benefits were directly noticed and translated to mega cost reductions, yet the challenge still lies in implementing on a real time project to monitor the differences on a gradual basis throughout the project execution phase of how the decision-making process would differ if managers applied the Mitigation (Cost) Controller and not the classical approach. Therefore, the goals of the development project at hand are two-fold: one is to test the effectiveness of the Mitigation (Cost) Controller and the second is to test the willingness of project managers to work with it.

The project presented in this document is going to explore the development of the Mitigation (Cost) Controller tool on a real time project and within a system of constraints built around multiple criteria constraints that stem from stakeholder requirements. In addition, the limitations of the said tool are assessed to suggest more features that can be dealt with in future enhancement of this tool.

Development Context

To better understand the context and the reasons the Mitigation (Cost) Controller is developed, the following sections present the gap in literature and practice which create development needs for practitioners and increases demand for an optimization tool. Furthermore, the next section includes the development statement and the relevance of the tool, both theoretically and practically.

Development Gap

Risk events take place in every construction or infrastructure project. Adopting a proactive behaviour is key in minimizing the impact and associated cost that comes with the occurrence of a negative risk (KARTHIK et al., 2017). Risks could cause an impact in any of the project's phases (planning, design, execution…). The extent of how early the risk event is anticipated determines how severe the outcome is on the project timeline (Kaliprasad, 2006).

Traditionally, corrective mitigation measures are implemented during the execution phase to ensure that the required probability of meeting the project overall cost is consistent throughout the project lifecycle (van & Binnekamp, 2011). In a more proactive manner, probabilistic budgeting is applied that would, after a series of Monte Carlo simulations, obtain a mitigation strategy that would meet the desired probability for within budget completion of the project (Leontaris et al., 2019).

However, such a method is considered inefficient as it's based on an iterative process of finding the least cost without factoring in the human behaviour. The latter, instead, would represent the role of the project managers, who would work backwards in a **goal-oriented manner** to not only achieve the desired probability, but achieve it with the **optimal mitigation strategy** (Kammouh et al., 2021).

As mentioned in the previous sub-section, the increase in market competitiveness led to more stringent timelines and tighter budgets which directly leads to a demand on more efficient and innovative solutions. In our context, the search for projects' mitigation strategies to preserve timelines and budgets should be more pragmatic and oriented towards maximizing project value.

The MitC software was thus developed at the Faculty of Civil Engineering at TU Delft. It is a software application that follows a probabilistic approach in project scheduling and automates the search for an optimized mitigation strategy with the biggest delay reduction at the least possible cost (Kammouh et al., 2021). Nevertheless, MitC still has several limitations including that decreasing the project's schedule comes at the expense of a single criterion represented by financial cost.

Accordingly, the development of a tool that optimizes project's budgets on a multi-criteria basis that incorporates several constraints other than cost and applying it on a real time project is necessary to establish more optimized approaches towards project budgeting. The problem statement of this development project is therefore:

The construction and infrastructure industry has underperformed in relevance to the specified timelines and constrained budgets throughout the years according to literature. This is attributed mainly to complexities leading to risks that ultimately impact the target project budget and with it the associated time at completion. The absence of an efficient tool that automates the search for the most optimal mitigation measures also contributes to the aforementioned problem. Optimizing the current method to choose risk mitigation strategies is a window of opportunity to improve project performance.

The project at hand aims to develop innovative tools that allow the optimization of the choice of risk mitigation strategies. The former can be achieved by incorporating multiple criteria in the optimization problem in an automated way that would reflect the project managers' real time behaviour.

Development needs

As described in previous sections, maximizing project value is directly related to minimizing the impact of faced risks which is dependent on optimizing the risk mitigation strategy. Such a strategy should incorporate the human behaviour i.e., a goal-oriented behaviour. Project managers should work backwords from the desired target budget to their selection of the adopted mitigation strategy.

Ultimately, the core objective of this study is to develop a Mitigation Cost Controller that would optimize project budgets while incorporating a multi-criteria assessment of negative impacts. Multi-criteria constraints involve all trade-offs a construction project might face to stay within budget like and not restricted to time delays, quality deficiencies, environmental impact and noise disturbances. Such an approach would enable project budgeting enhancement.

Subsequently, it exposes project managers to leverage such an opportunity in their project planning and apply more efficient risk mitigation strategies in construction and infrastructure projects through an automated decision support tool that eliminates the trial-and-error procedure they carry out and still reflects their mindset and behaviour to achieve the desired budget at the least negative impact.

Development Statement

By taking into consideration the development gap and development needs, the development statement is formulated as follows:

"To develop a project management decision-support tool that would automate the selection of an optimal mitigation strategy to keep construction and infrastructure projects on budget at completion while taking into consideration stakeholder requirements that best fit that project's constraints."

Scientific Relevance

From a theoretical viewpoint, the project at hand can provide an innovative more efficient probabilistic approach in adopting risk mitigation strategies. It would still provide a similar model of Monte Carlo simulations but would introduce a shift in the behaviour of managers. Such a shift is represented by the goal-oriented behaviour that is the core element of how the tool works and how it outperforms the classical approach. The study at hand also sheds light on additional considerations that can maximize project value by assessing multiple criteria constraints at once. Subsequently, this step can lead managers to take additional factors into account while mitigating risks faced in projects.

Industrial Relevance

The aim of the Mitigation (Cost) Controller(MitCC) is to be adopted as a support tool by project managers in construction budgeting primarily and ultimately in industrial budgeting as a whole. The tool allows project managers to take decisions concerning the selection of mitigation strategies in a fast, yet accurate manner (Kammouh et al., 2021).

Translating the above into more concrete day to day activities, it can allow for:

- Enhanced cost estimations early in the project lifecycle throughout the tender phase by better anticipation of risks.
- Reduced negative effects in adopting the mitigation strategies to combat the sudden risks faced throughout the execution phase.

In a more focused context, the development of the Mitigation Controller can ultimately lead to an increased chance of project success by incorporating the shortcomings and benefits into the framework managers use to mitigate their risks. Such a step could change the current reactive behaviour towards risk to a more proactive one leading to several benefits at the organizational level. For instance, possible business growth and enhanced reputation due to the noticeable cost reductions and increased project value.

Development Methods

Throughout this chapter, the methods used to further develop the Mitigation Controller are elaborated. Accordingly, it's essential to define the boundaries of the project and its scope.

Scope

To ensure the timely completion of the development project within the given time frame, it's important to delineate the scope. The development will be conducted in collaboration with the company **Drees & Sommer.** The main aim, as previously described, is to further develop the Mitigation Controller for costs, and apply it on a real-time ongoing project. The validation process is composed of a comparative assessment of the tool at hand with tools currently available in the market. However, it's worthy to point out that the comparison will be only restricted to the comparison at the level of limitations and benefits of the adopted new software. A more thorough analysis concerning any additional features that tool might fail to accommodate like resource limitation is out of the scope. After the comparative assessment, the robustness of the model will be tested. Finally, the usefulness will be evaluated with practitioners.

Methodology

To better understand the required steps needed to ensure the accurate development of the tool, it's important to identify the nature of project at hand. It is a development that aims at enabling results by developing new products that would improve organizational performance by the means of modelling and simulation as well as experimenting by validation. In the project's context, the Mitigation Controller aims at automating and optimizing the selection of mitigation measures in construction projects to keep them within budget using a series of Monte Carlo simulations. The effectiveness of the tool is evaluated by the validation carried out on a real time project at the company.

By the means of google scholar and the TU Delft library, a literature study is primarily carried out to identify the gaps present in literature. In addition, a desk research is carried out at the company to better understand the basis on which mitigations strategies are chosen in practice. Online conducted interviews are analysed using Qualitative Content Analysis (QCA) that aided int their transcription and clustering the common terms (Schreier, 2019). The company research carried out provided insights on the constraints that shall be adopted in the program as well as the main assumptions that need to be taken while construction the mathematical model.

The coding of the tool at hand is developed using MATLAB 2019b and the analysis is done through solving a linear programming optimization problem. In terms of the input, it is constructed using Microsoft Excel with the aid of TETRA, a preference-based modelling tool that is used to calculate the aggregated average of the negative impacts criteria. As for the development validation, it is carried out by demonstrating the results to the relevant project managers and comparing their approach to the output of the tool. Furthermore, the validation is also composed by testing against the model's needs and requirements as well its objectives.

An overview of the methodology followed to fulfil the objective and ensure all needs are answered is depicted in the figure below. The development of the Mitigation (Cost) Controller will go through 4 phases: The initial exploration phase, the data collection and code building phase, the model verification as well as its validation.

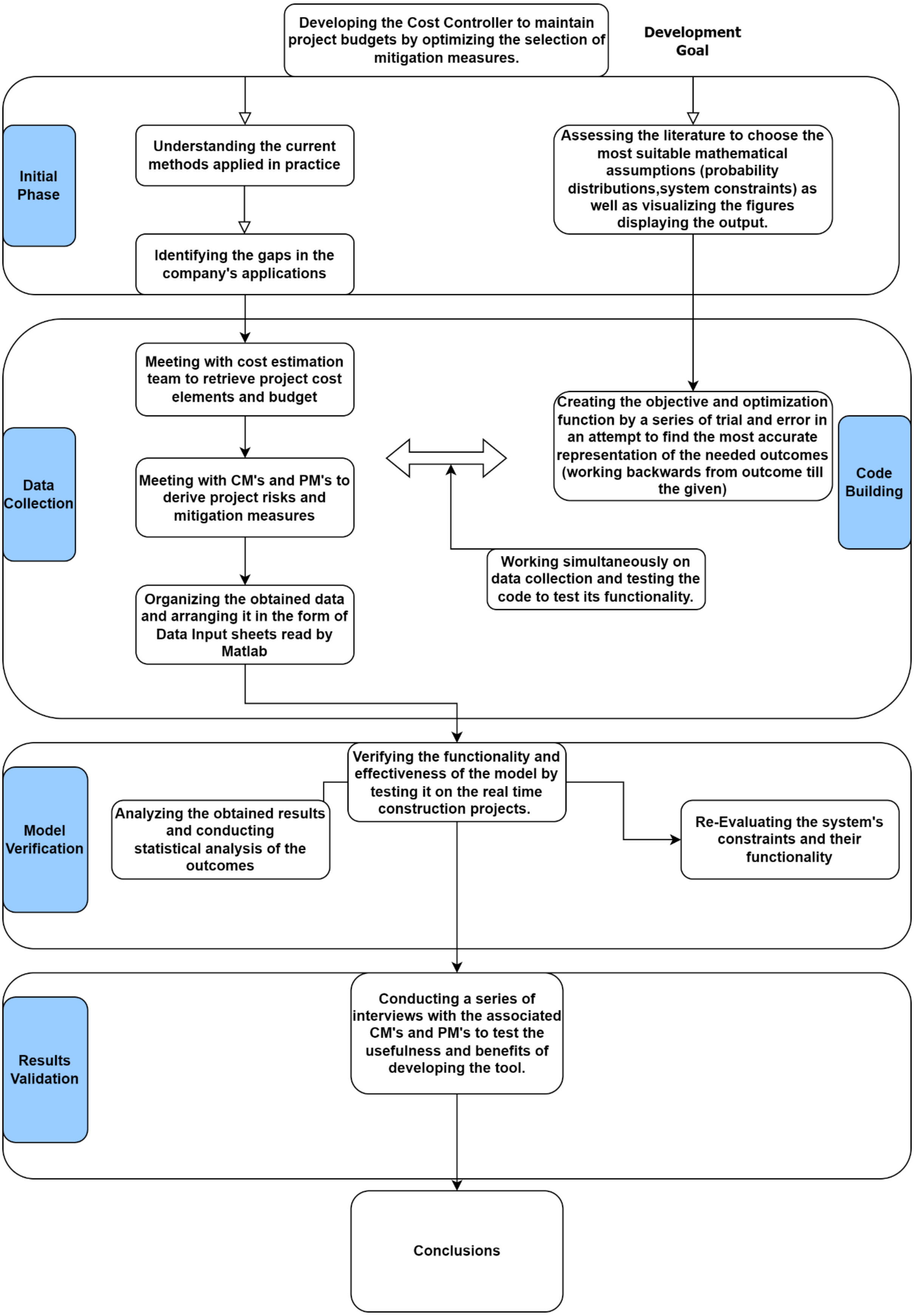

Figure 1 Development methods followed for creation of Mitigation (Cost) Controller

Limitations on development methods

Every project has its own limitations dictated by the scope and the methodology. The constraints posed by this development are divided into two parts: the first related to literature and the second to the tool under study (Mitigation Controller) itself. Both limitations are summarized below:

- Literature Limitations:

  There are insufficient studies available on the nature of how current tools work from an operational and systematic level in iterating and finding the best possible mitigation measures. Research done is mainly focused on the causes of risks and their impacts. With relevance to mitigation measures, the only available studies focus on the effect of proactive project planning at the level of pre-execution phase and the results of it rather than an explicit mechanism of how to achieve proactive planning. Such a gap can be considered as double-edged sword. On one hand, it doesn't allow us to extensively explore the literature about the back-end structure of available tools, yet it's also an opportunity to formulate our own assumptions and be innovative in developing new tools, which is the core of this validation study.
- Empirical Assessment Limitations:

  Structured interviews with project managers are arranged for data collection pertaining to risk registers and mitigation measures. Risk registers will be used to input the risks along with their respective probability of occurrence and subsequently their impact. The choice of project managers will be based on managers who are working or have worked on projects identical to the project at hand. Since data collection will be partially qualitative through interviews and evidence based with regards to risk registers, the most common risks will be included and not based on a database containing them. Such an approach might lead to a loss of accuracy since some risks might be neglected. Likewise, a similar approach is followed to pile up the mitigation measures with their respective capacities and costs.

  However, this approach is necessary to deliver results in the required timeframe and within the study's scope.
- Tool Limitations:

  The validation is performed based on the latest released version of the tool. One of the shortcomings was the omission of determining the project's critical path. Therefore, the analysis conducted on the negative impacts of measures is on lost time not project delay.

Chapter II: Mitigation Controller Paper

The aim after the completion of this project is to publish a journal article on the work that has been established. In this chapter, a fully integrated version of this article is demonstrated. The content of the following document is per the latest update done on the 10^{th} of February 2022.

Mitigation Controller: A Multi-Criteria Optimizations & Simulations Approach to Keep Construction Projects Within Budget

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Abstract

The construction and infrastructure industry has witnessed an increase in the need for an optimized mitigation strategy to combat schedule and cost overruns amid the rise in market competitiveness and more strict timelines and budgets. Moreover, projects nowadays are more complex in terms their scope and requirements which ultimately drives more innovative and efficient solutions to enhance project risk mitigation. Typically, Monte Carlo (MC) simulations with different combinations of mitigation measures are performed until a random set of measures is chosen to satisfy the targeted budget. Several attempts aimed at optimizing around different objective functions to obtain more efficient strategies that would demonstrate the dynamics faced on the construction sites(Safaeian et al., 2022). The main flaw of all attempts were the absence of the goal-oriented control behavior of the project manager who would only opt to the optimal mitigation strategy given a risk event and cost overrun. The closest attempt was demonstrated in the objective functions of MitC developed to keep projects within schedule given a set of optimized mitigation strategies (Kammouh et al., 2021). However, the aforementioned tool solely addresses the selection of mitigation measures in the case of project delays affecting a strict delivery date with a trade-off restricted to one criterion: cost. The development in this document demonstrates a tool with broader functionalities that aims at selecting an optimized strategy to keep the project within budget yet with further additional features that extend its usefulness to a multi-criteria approach that involves time delays, environmental impacts as well as noise disturbance. The usefulness of the Mitigation controller for cost is demonstrated using a real case of a construction project in the Netherlands with the analysis performed on the go yielding significant negative impact savings relative to current approaches used to maintain the project's budget.

Keywords: risk event; mitigation measure; stochastic budgeting; cost-optimization , probabilistic budgeting

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Introduction

It's no secret that project success is dependent on finishing within the specified schedule and planned budget at the best possible quality. However, all the former factors are directly affected by numerous unplanned risks(Alkaissy et al., 2020; Kabirifar & Mojtahedi, 2019). Risks though are main characteristics of every project and are only aggravated with the increase of dynamics and complexities associated with every project(Ildarabadi & Alamatian, 2021). To reduce project failures, all factors must be considered through the planning of the project and through the management of the execution phase. In theory, corrective mitigation measures are typically applied against faced risks to maintain the probability of timely and within budget completion of construction projects. Such measures are highlighted and implemented during execution(Van Gunsteren et al., 2011). Nevertheless, the key to better evaluate and manage the risks is to use the right risk management strategies(Gunduz & Yahya, 2018).

However, available methods and tools fail in different manners in selecting an efficient and optimized mitigation strategy. The earliest efforts around probabilistic budgeting were done by Ben-David and Raz who developed a model that would select the mitigation strategy by using an objective function that minimizes the total expected cost of risks. Their efforts paved the way for further assumptions added to their model from determining risk and response correlations to better estimate the impact to the latest additions of evaluating risk interactions and optimizing around an exponential utility function that maximizes around the risk response (Safaeian et al., 2022). In short, the previous mentioned attempts follow a series of probabilistic simulations to specify the overall project cost with a certain probability of success. Such a method is based on an iterative process finding the right measures to satisfy the required probability of success (Budruk et al., 2019). However, as the scope and size of the project increases, this approach can be highly ineffective as the set of cost elements, risks and mitigation measures will increase**.**

Most importantly, the methods mentioned above fail in the inclusion of the human goal-oriented behaviour of working backwords from a specified budget and selecting the most optimal mitigation measures to attain the desired costs with the least possible negative effect. It leaves the project manager with no flexibility and control over the choice of the mitigation strategy, thus failing to adopt an optimized choice of measures. The construction of the Mitigation Controller for project schedule optimization succeeded in demonstrating the goal-oriented behaviour in modelling. Accordingly, it constituted the motivation to develop the MitC tool for cost controller that aims at optimizing the selection of an efficient risk mitigation strategy for projects (Kammouh et al., 2021) to keep construction projects on budget. It stems from the studies conducted to identify cost escalations in projects and finding their subsequent mitigation measures to enhance the probability of project success (Viswanathan et al., 2020) and extends to mimic the optimization function used in the initial version of MitC. Furthermore, the mitigation cost controller extends to also include a multi-criteria optimization approach where the negative effects of applying mitigation measure are not restricted to a cost/time trade-off. The optimization function used maximizes effectiveness which is the ratio of cost reduction to aggregated average negative effect. The latter involves the evaluation of time delay, noise disturbance as well as environmental impact of the implementation of each measure. Such additional functionalities are believed to emphasize the goal-oriented behaviour further and constitute a more accurate representation of the project complexities which would yield more efficient selections of mitigation strategies.

It’s crucial to obtain the closest representations of project complexities as the Mitigation controller tool aims at supporting project manager’s decisions with relevance to two project stages. The first one is during the tender phase to achieve more sound cost estimates. The second is during execution to act on the most important mitigation measures and achieve more control over their respective negative effects.

The sections below demonstrate how can the former ideas be achieved and utilized. The next section outlines the main mathematical assumptions of the tool and its considerations. The demonstration section describes the real time case study the tool was implemented on and later validated and discusses the obtained results and benefits. The final sections also highlight the limitations faced and suggest further features that could yield to enhanced future developments

MitC assumptions and considerations

The sections below highlight the major assumptions taken to build the mathematical logic of the code as well as the certain limitations imposed by the first release of the tool.

Cost Uncertainty of Project Elements

Project budgeting, just like scheduling, can follow two approaches: a deterministic and probabilistic one. The common practices involve taking into consideration only deterministic values by assigning one value, x where $x \in \mathbb{N}^{+}$, to each cost element. However, such a method could directly lead to a misjudgment and error in calculating the project's final budget due to the absence of equating the item's uncertainty. Therefore, calculating the project costs follows a probabilistic approach in the Mitigation (Cost) Controller (MitCC) to minimize estimation error. The typical method to estimate costs or durations and consider uncertainty is the PERT (Program Evaluation and Review Technique) method (del Pico, 2013).It is a case of continuous probability distribution and is calculated as follows:

$$E[X] = \frac{a + 4b + c}{6} = \mu$$

(1)

where E[X} is the expected value of a cost element, a is the optimistic value (minimum), b is most-likely value , and c is the pessimistic value (maximum) that a random variable can take. With the definition of the variables, the probability density function of the PERT distribution is now derived for each cost item in the form $f(cost_i\ ; a,b,c)$. It's worthy to point out that the cost calculated in the within the continuous PERT distribution domain is transformed into the discrete one by approximation to the nearest natural number.

Risk Events

Every construction project faces risks that either impact the cost, time or quality of the project. To simplify the variables and assess the effectiveness of the cost controller as a tool used to optimize the budgeting of a project, only risks that directly impact the cost and lead to an overrun are assessed. Neglecting the quantification of these risks, whether in terms of impact or probability, in the planning or execution phase leads to project delays and/or cost overruns. The CostController accounts for the aforementioned risk events by the following logic and method; every risk item is associated with a random variable C that denotes the cost impact caused by a risk event *e*. The probability distribution of his random variable is a mixed discrete-continuous distribution, expressed as follows:

$$f(C_e; p_e, a_e, b_e, c_e) = \begin{cases} 1 - p_e & \text{if} \quad X_e = 0 \\ f(C_e^*; a_e, b_e, c_e)p_e & \text{if} \quad X_e = 1' \end{cases}$$

2

where $X_e = \{0,1\}$ is a discrete random variable that represents the occurrence (or non-occurrence) of risk event e. If risk event e occurs, X_e takes the value 1 with probability p_e, while it takes 0 with probability $q_e = 1 - p_e$ if a risk event does not occur; that is,

$$f(X_e; p_e) = \begin{cases} q_e = 1 - p_e & \text{if} \quad X_e = 0 \\ p_e & \text{if} \quad X_e = 1' \end{cases}$$

3

while C_e^* is the outcome of the random variable $C_e^* \in \mathbb{R}^+$, which denotes the cost impact caused by a risk event e given that the risk event occurs (i.e., $X_e = 1$). C_e^* is assumed to follow the Beta-PERT distribution with a probability density function $f(C_e^*; a_e, b_e, c_e)$, where a_e, b_e, and c_e are the minimum, most-likely, and maximum outcomes, respectively.

Mitigation Measures

In a similar manner, mitigation measures are also calculated following the BETA-PERT distribution. However, each mitigation measures is associated with a mitigation capacity, that is the maximum cost reduction held by each measure. Each measure, thereby, has a probability density function and the capacity obtained is transformed to the discrete domain.

Multi-Criteria Assessment of Mitigations Negative Impact

To reduce impact of cost overruns fired from risks, mitigation measures are applied. The latter, however, carry a negative effect in the form of quality deficiency or a time delay. In the first part of the analysis, time delay is the only trade-off taken into consideration. The delay of mitigation is determined by the type of mitigation measure used. Some mitigation strategies include involving the client in the design early to ensure all stakeholders are aligned on the design process. Such a step doesn’t carry major cost additions yet requires additional effort by the project team and hence more time. On the other hand, quality deficiencies or other qualitative measures like noise disturbance or environmental impact of the adopted measures can be taken into consideration to give a broader overview and a more accurate representation of real-life cases.

Accordingly, each mitigation measures carries alongside the stochastic values of the cost reduction and deterministic values for the respective measure's negative effects. In the case prescribed below, time delay, noise disturbance and environmental impact were the three negative effects taken into consideration as per the recommendation of the project managers overseeing the execution on site and involved in stakeholder management of the demonstrative case displayed below.

Rating-Based Input

For the negative impacts explained above, ratings on a scale of 1 to 5 were given to each negative impact, with 1 carrying the least negative impact on the project and 5 the relative maximum impact. Such a scaling system was adopted to unify the measurement units and maintain consistency across the impact assessment, since the three assessed criteria are of different units. However, to better understand the context of the used scale, the following section elaborates on the mapping of the individual negative impact space to the rating scale space.

Mapping

As explained previously, each negative impact corresponds to a unique unit of measurement and is then reflected in the ratings scale. For instance, with relevance to the delay effect, a rating of 1 yields a delay of one week and a rating of 5 yields a delay of 6 weeks. The ratings in between correspond to an interpolation among both values. The determination of the best case and worst-case rating isn't universal and is determined based on a project basis. It is a relative measure and is only determined after calculating the delay corresponding to each mitigation measure. After that, the best and worst performing measures in that criteria are highlighted, and the ratings are drawn out. Similarly, the noise disturbance ratings are calculated. X db correspond to a rating of 1 and Y db correspond to a rating of 5 where Y>X. As for the environmental impact, 1 corresponds to least CO_2 emissions with X kg/CO_2 produced and 5 to Y kg/CO_2 produced where Y>X.

Preference Based Measurements

Another intermediatory step before running the analysis is to calculate the aggregated average of the multi-criteria using TETRA preference-based modelling software. At first glance, it would suggest that the average negative impact would be composed of calculating the weighted average of the individual criteria, yet from a mathematical perspective this is considered a modelling error as multiplying and adding operations are not defined within this scale. Such a step would take us from the vector space to the space with no absolute zeroes. The more accurate way is thus finding the aggregated preference which would minimize the least squares difference between the ultimate preference and each score's relative space (Barzilai et al., 2010). Such a step would yield more accurate representations of the average. Accordingly, the system will be projected from the 0-5 space to the 0-100 as shown in the figure 3 below with the only exception from TETRA is that the scale used in the latter is flipped with 0 assumed the best and 100 the worst performing rating.

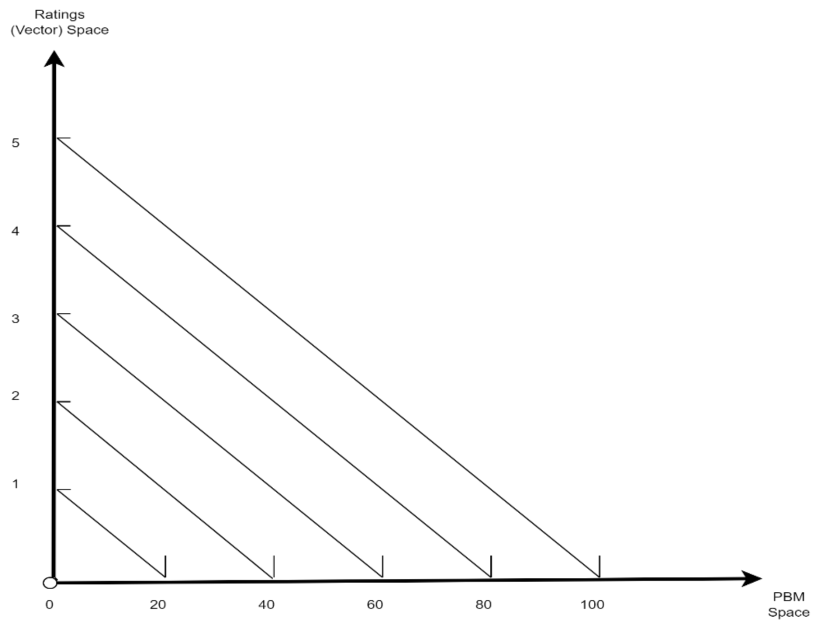


Figure 2 Translation from the vector to the no absolute zero space

Relations between construction activities, mitigation measures, and risk events

Mitigation measures are used to mitigate cost overruns so that the project can be completed within budget. Implementing a mitigation measures signifies the need for additional time to avoid resources addition, quality diffencies , etc. The MitCC couples mitigation measures with project activities in such a way that one mitigation measure can affect more than one activity. The relations between the mitigation measures and the project activities are given by the relation matrix in Eq1. The relation parameter $r_{i,j}$ takes the value of *1* when mitigation measure *j* intervenes upon activity *i*, zero otherwise.

$$[r_{ij}] = \begin{bmatrix} r_{11} & \cdots & r_{1J} \\ \vdots & \ddots & \vdots \\ r_{I1} & \cdots & r_{IJ} \end{bmatrix}, \qquad (1)$$

where *I* is the number of activities and *J* is the number of mitigation measures.

Similarly, each risk event can impact several activities at the same time. The relation parameter s_{ie} takes the value of *1* when risk event *e* affects activity *i* and zero otherwise. The corresponding relation matrix is expressed as follows:

$$[s_{ie}] = \begin{bmatrix} s_{11} & \cdots & s_{1E} \\ \vdots & \ddots & \vdots \\ s_{I1} & \cdots & s_{IE} \end{bmatrix}, \tag{2}$$

where *E* is the total number of potential risk events.

Monte Carlo Simulations Approach

The primary added value brought forward by the Cost Controller is the ability to include the uncertainties arising from the variables estimation in calculating the projects overall budget. Such a functionality is made possible by using Monte Carlo simulations that are dependent on the continuous random sampling that would demonstrate the stochastic behavior of all random variables. The approach followed to obtain the optimal strategy using Monte Carlo simulations is displayed in the flow chart below. Figure 3 highlights the procedures followed which are divided into 3 main parts. The initial part (Steps 1-3) is evolved around the user input and importing it into the model. The core section (Steps 4-12) consists of the calculations done in each iteration. Finally, the last part consisting of step 13 is concerned with the collection and analysis.

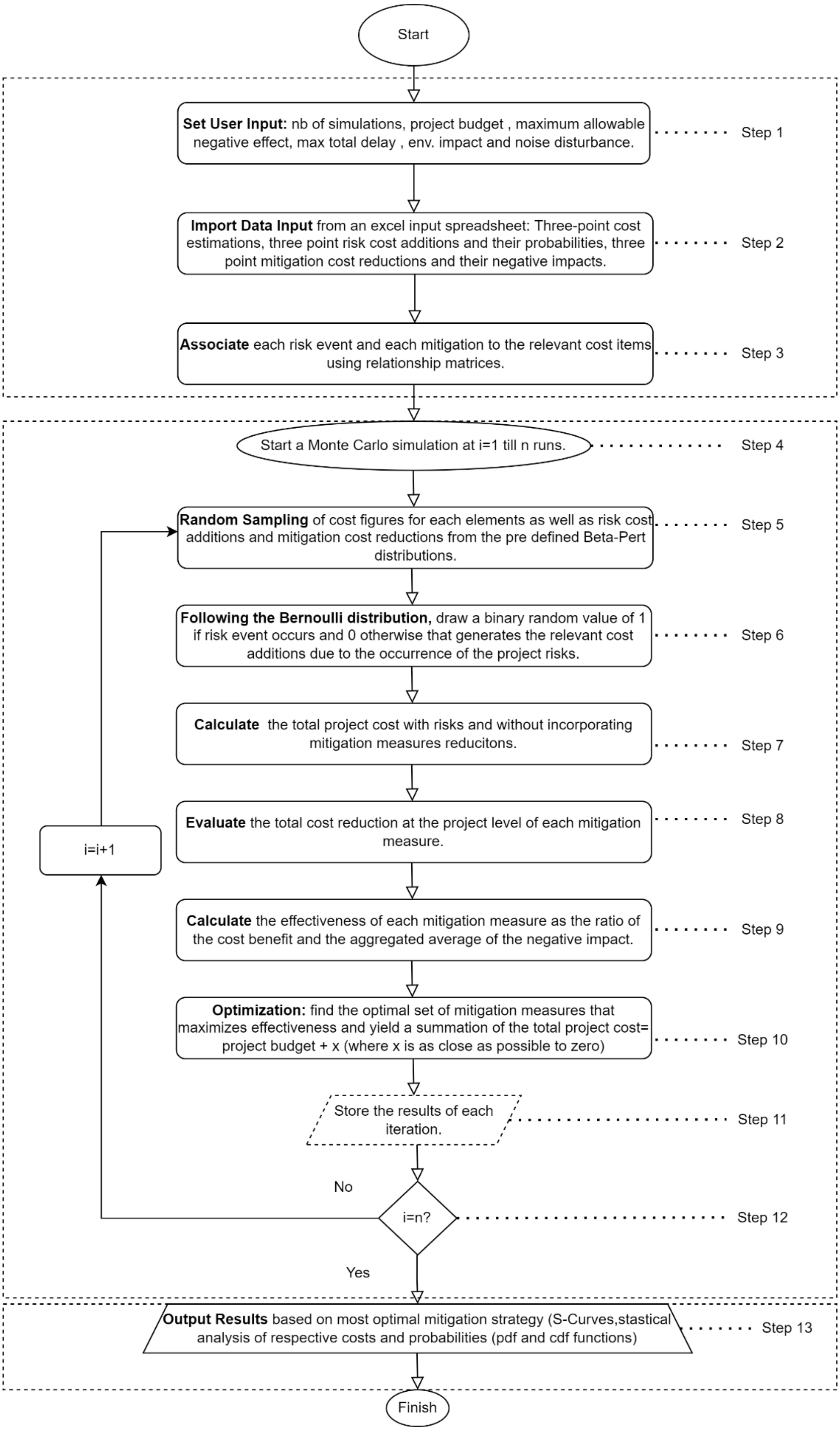


Figure 3 Flowchart of applying Mitigation (Cost) Controller to cost items of construction project

The following steps highlight the simulations approach followed.

Steps 1 and 2 are mainly focused on obtaining the user input shown in figure 5 below concerning the system's constraints. Project cost related data are arranged in a computer-readable format and include the following sets of information about cost of elements, possible risk events and the corresponding mitigation measures:

- Three estimates for the cost of each item: a pessimistic, most likely, and optimistic.
- Three estimates for possible cost reduction of each mitigation measure (positive effect).
- The negative effects associated with every mitigation measure in the form of ratings on a scale of 1 to 5. For instance, the lost time, noise disturbance and environmental impact.
- The aggregated average of the mitigation measure's negative impacts on a scale from 0 to 100 obtained from TETRA preference-based modelling.
- Three estimates for impact of each risk event, if occurred, shown in the form of additional cost per cost element.
- The probability of occurrence for each risk event.
- The relationships between the mitigation measures and the cost items: the cost elements that are directly reduced due to the implementation of the measures.
- The relationships between the risk events and the cost items: the elements that are impacted by the occurrence of risk events.
- The planned budget of the construction project or target budget.
- The maximum desired average of negative impact of the mitigation strategy chosen.
- The maximum allowable individual total lost time, noise disturbance and environmental impact.

A	B	C	D	E
1	2	3	4	5
Activity ID	Activity description	Cost		
		Optimistic	Likely	Pessimistic
1	Contract Date	0	0	0
2	Financial Close	0	0	0
3	Design	47250	52500	60375
4	General Preparation Works	112066	120566	130000
5	Partioning	427004	478375	520000
6	Flooring	119383	133830	141500
7	Painting	30000	34685	54273
8	Mechanical Installation & Plumbing	731326	769848	780000
9	Electrical Installation	98752	163971	180000
10	Data & Servers Installations	45000	52170	80096

R	S	T	U	V	W	X
18	19	20	21	22	23	24
Risk event ID	Risk Event Description	Risk Event Cost			Relationship	Probability
		Minimum	Most likel	maximum		
1	Mechanical Design Plans rejected.	45,000	50,000	53,000	3	0.25
2	Light reflection of finishes and furniture	11,000	15,000	17,000	15	0.15
3	VOC emissions from materials used too l	31,000	40,000	45,000	6	0.15
4	Late delivery of glass and metal element:	38,000	50,000	53,500	19	0.2
5	Unexpected Asbestos	4000	5,000	5,500	7	0.05
6	Covid-19 lockdown (Labour shortage)	10,000	20,000	24,000	25	0.25
7	Labour affected due to market uncertaint	10,000	20,000	24,000	5	0.2
8	Inaccurate and loss of information due t	14,000	15,000	21,000	4	0.15
9	Dust levels exceeded when works progre	2,500	4,500	5,000	8	0.15
10	Failure to reuse existing furniture	4,700	5,000	6,500	17	0.1

F	G	H	I	J	L	M	N	P	Q
6	7	8	9	10	12	13	14	16	17
Mitigation ID	Mitigation measure description	Positive Effect Mitigation Cost			Negative Effect(1->5)			Aggregated Average (TETRA)	Relationship
		Minimum	Most likel	maximum	Delay	Environmental	Noise Levels		
1	Engage Client on each design ph	21,500	25000	28,000	4	1	1	37.3	3
2	Re-asses Plans & Install Needed	3,000	5000	6,000	4	1	1	37.3	15
3	Assign Quality Control team for	8,500	10000	14,000	4	1	1	37.3	6
4	Carry on at lower productivity ra	4,000	5000	5,500	4	1	3	59.1	19
5	Monitor Closely each elements o	6,000	7000	9,000	5	1	1	50	7
6	Carry on with available teams	5,500	7000	8,000	4	1	2	45.2	25
7	Work with unskilled labour	7,000	10000	14,000	5	1	2	58.1	4
8	Conduct Workshops to make su	7,000	8000	8,750	4	1	1	37.3	4
9	Minimize activities on occupied s	2,600	3000	4,500	3	2	2	39.4	8
10	Asses furtniture and order only c	1,750	2000	2,500	4	3	2	58.8	17

Figure 4 User Input from Excel spreadsheet

In **Step 3**, the cost elements are associated with the relevant risks and mitigation measures. Accordingly, the cost items are directly linked with the risks that lead to additional cost and mitigation measures that reduce the cost of the said item.

In **Step 4**, the MC simulation initiates after the definition of a loop of *n* iterations chosen by the user. The counter is set to 1 and the tool runs till the number of simulations defined by the user is obtained.

In **Step 5**, from pre-defined beta-PERT distributions, the three point estimates of costs, risk cost additions and mitigations measures' cost reductions highlighted in step 1, are randomly drawn.

In **Step 6**, following the Bernoulli distribution, a random binary variable of 1 or 0 is drawn for every risk event with its associated probability of occurrence and is given a value of 1 if it takes place (probability of success) and 0 elsewhere.

In **Step 7**, after the sampling of the random variables mentioned previously in steps 5 and 6 , the total cost of the project is calculated in two cases: with and without taking into consideration the mitigation measures.

Step 8 is evolved around calculating the cost reduction posed by the occurrence of each mitigation measure.

Following from the previous steps, **step 9** highlights the final step before the initiation of the optimization and is composed of calculating the effectiveness of each mitigation measure, which is defined as the ratio of the cost reduction and the aggregated average of negative impact of each mitigation measure.

In **Step 10**, optimization is carried out and the optimal set of mitigation measures that would maximize effectiveness is selected. Maximizing effectiveness(ratio of cost benefit to negative impact) is based on maximizing the cost benefit or minimizing the negative impact of each measure or both. The next section further elaborates on the mathematical formulation of the optimization problem.

In **Step 12,** the results of each iteration including the optimal mitigation strategy, the cost reduction and the overall project cost are stored in the memory.

Step 13 is the final step of the MC simulation after which the steps 4-12 are repeated until the number of simulations inputted by the user is reached.

The **final step (14)** is composed of generating the outputs of the optimal mitigation strategy with the corresponding results of the total project cost , the chosen mitigation measures , and their negative impact distributions along with additional statistical insights as shown in the results section.

Optimization Problem

Neglecting the human behaviour in predicting the project's overall durations or costs is the main motivation to develop the Mitigation Controller(Kammouh et al., 2021) primarily and the Mitigation (Cost) Controller in this following paper. Accordingly, to better reflect this behaviour it's crucial to understand how project managers react to possible cost overruns throughout the project lifecycle. Practitioners typically apply sets of mitigation measures to combat the fired risks on a trial-and-error basis to obtain the maximum possible cost reduction. Therefore, solving an optimization function in every Monte simulation for a defined number of simulations includes the human behaviour of a project manager in the suggested model. Ultimately, solving an optimization problem for each simulation aims at selecting the optimal mitigation strategy. The latter is identified as the strategy that yields maximum mitigation effectiveness, which is defined as the ratio of cost reduction to aggregated average negative effect. It's worthy of notice that if two or more mitigation strategies yield the same effectiveness, the one with the biggest cost reduction is chosen. In addition, if no set of measures results in obtaining the planned budget, the solution with the least difference to budget is chosen as depicted in figure 3 below.

In a mathematical context, each cost element is denoted an ID i where $i \in \mathbb{N}^+$ and constituted the set of all cost items = $\{1,2,\ldots,i\}$. The summation of all cost items yields the total target cost of the project C_{target}. Any cost overruns at the activity or item level directly leads to an overall cost overrun that should be mitigated to maintain the project budget. Accordingly, corrective measures are in place to decrease the individual costs at the item level and subsequently decrease the overall project cost to reach the planned budget desired by the project manager. The set of measures is denoted by J where $J \in \mathbb{N}^+$ and is = {1,2,….,J}. The variable $x \in \{0,1\}$ denotes whether the mitigation measure is applied or not.

In each Monte Carlo simulation, a measure j reduces an item i by a certain cost, $c_r \in \mathbb{N}^*$. The trade off, though, for this cost reduction, is a negative impact ($N_i \in \mathbb{R}^+$) composed of the aggregated average of three criteria: lost time, noise disturbance and environmental impact. The objective is to maximize the effectiveness, thus, to maximize the cost reduction and to minimize the negative impact. Figure 3 below highlights the logic the optimization problem is based on and the possible outcomes of running the simulations. The first line highlights the project's overall cost including the risks and without mitigation. The second line outlines the cost reduction from the overall total cost to the optimized total cost that is equal to the planned budget by applying the most optimal mitigation strategy that maximizes the effectiveness ratio. As for the third scenario, if it's mathematically impossible to attain an optimized cost = planned budget, a variable φ is added and is defined as the residual additional cost that is still needed to be reduced to attain the planned budget. Such a possibility is possible if the planned budget is too optimistic, or the boundary constraints of the optimization function are too stringent with relevance to the mitigations measures 'capacity. In the final scenario (scenario 4), the total cost is less than the inputted planned budget and accordingly no strategy is implemented after MC simulations as no action is required to mitigate the budget.

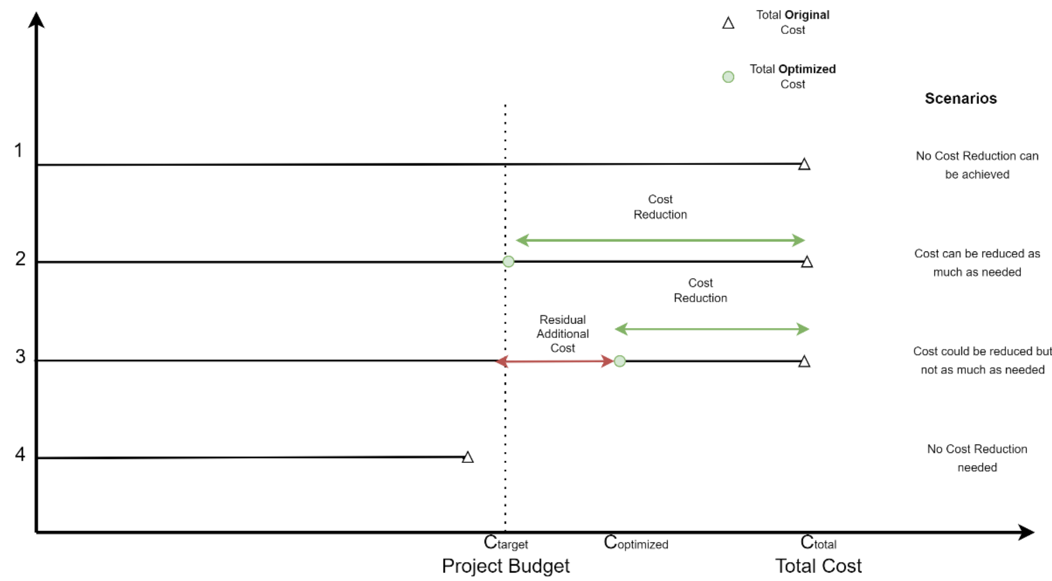


Figure 5 Scenarios and possible outcomes of the optimization problem

It's worthy of notice that the assumptions taken in the mathematical model don't include any incentives that might be placed by the client in the form of rewards. For example, in design and build contracts or cost-plus contracts, a guaranteed maximum price (GMP) is agreed upon between the contractor and client and one form of rewards in this scheme is splitting the difference between the GMP and total cost if the latter is significantly less than the GMP. For simplification purposes, the scenarios below and mathematical logic used to create the code don't include such specific cases.

Objective function

The optimization problem explained above can be expressed in terms of the objective function as follows:

$$\min_{X,\Delta} \sum_{j\in\mathcal{J}} \frac{1}{\exp{(Eff_j)}} x_j + (\delta \times \Delta)$$

where δ: positive weighting factor (a relatively high number in the order of 10^8) , $\Delta \in \mathbb{N}$ and can be defined as the project's cost overrun if the mitigation measures are not adequate to guarantee the specified project budget. x_j is a binary variable (0,1) that represents the implementation of a mitigation measure j. Eff_j is the effectiveness of each implemented measure j and is equal to:

$$\mathbf{Eff}_j = \sum_{j=1}^{J} \frac{c_{rj}}{N_j}$$

This measure is the primary comparative metric used in selecting the most optimal mitigation strategy. It allows for a fair comparison among the different corrective measures as it measures the ratio of the cost reduction to the relevant aggregated average negative impact of each measure j. That is, it avoids a modelling error of choosing the biggest cost reduction that might be accompanied by a bigger negative impact and prioritizes effectiveness over a single impact whether it was positive or negative.

With regards to the objective function, the first term results in the chosen optimal strategy to reduce the project cost to guarantee completion within budget at the least possible negative effect. It's worthy of notice that the function is structured to operate by minimizing the inverse of exponent of effectiveness rather than the invesre of effectiveness to prevent computational overflow linked with the zero values. Also for ease of calculations and within the computational constraints of the program , the function is structured to minimize the inverse of the exponential of effectiveness rather than maximizing effectiveness or its exponential directly.

As for the second term, it tackles the additional cost of the project over the planned budget in the case that measures in place aren't sufficient to maintain a within-budget completion. The cost overrun term (Δ) should intuitively be as small as possible and large weight should be placed on obtaining this result. That's why, the weighting factor δ is introduced and is at the scale of 10^8 to reflect this theoretical importance. In a mathematical context, the algorithm in this case will initially search for the most effective measures to reduce the project cost and attain the planned budget figure and if it fails to find the right measures the suggested strategy would be the one that minimizes the cost overrun i.e. the gap from the total cost to the budget.

Constraints

To ensure an accurate and an optimized solution that reflects the reality of dynamics faced on the project site is chosen, the following 6 constraints are laid out:

The first constraint in the equation below is to prevent the choice of measures with zero effectiveness:

$$\frac{1}{\exp(Eff_j)} x_j < 1 \;\forall j \in \mathrm{J}$$

The second constraint is directly related to the cost reduction of the project's budget. As mentioned previously, if the project budget can't be obtained due to the ineffectiveness of the available mitigation measures, the constraint is made flexible by the introduction the cost overrun differential Δ.

$$C_{total} - MitCost \leq C_{tar} + \Delta \quad \forall k \in \mathcal{K}$$

where $C_k^0$is the total current cost (before optimization) and $MitCost$ is the mitigation cost reduction given by:

$$MitCost \;= \sum_{j \in \mathcal{J}} m_j x_j \qquad \forall j \in \mathrm{J}$$

The final four constraints are all related to the bounds set on the negative impact carried by the implementation of the corrective set of measures. The third constraint is on the mean value of the aggregated average negative impact of the set of chosen measures.

$$mean\left(NI_{average_j}\right) \leq MaxNegEff_{average} \;\; \forall j \in \mathrm{J}$$

The remaining constraints are set to put an upper bound on the total negative impact per criteria. This is done to prevent obtaining measures with an allowable average value, yet with an extreme single criterion value. In some projects, there could be an upper limit on the noise disturbance caused in dB or a max cap on the CO_2 produced or the project manager might want to avoid having a bigger number of lost days on site. That being said the constraints are formulated as show below:

$$\sum_{j \in \mathcal{J}} NI_{time_j} x_j \leq MaxNegEff_{time_{total}} \quad \forall j \in \mathrm{J}$$

$$\sum_{j \in \mathcal{J}} NI_{noise_j} x_j \leq MaxNegEff_{noise_{total}} \quad \forall j \in \mathrm{J}$$

$$\sum_{j \in \mathcal{J}} NI_{envir_j} x_j \leq MaxNegEff_{envir_{total}} \quad \forall j \in \mathrm{J}$$

Demonstrative Case - Dutch Construction Project

The implementation of the Mitigation Controller on real time ongoing construction project is highlighted in the following section. The project is a rehabilitation of a retail and offices building in Amsterdam. The contractor was hired on a design and build contract and the demonstrated project is one of 4 buildings in the same geographical area to be executed by the same contractor. The project at hand faces a strict timeline and a stringent budget as the contractor accepted to take a project on a lower profitability rate for stakeholder satisfaction purposes regarding their client. To preserve confidentiality requirements, the name of the project and the contractor are omitted. Moreover, only the main cost elements are under consideration for the sake of simplicity. The project budget estimated by the cost control team before execution was found out to be 3,077,806 euros for this work package and this figure is deemed the Planned budget or target cost (C_{tar}) to be used in the analysis below. Such a figure can be maintained if no cost discrepancies occur over the course of the project execution phase. However, all cost elements are bound to fluctuate due to the uncertainty involved in cost estimation which can lead to an increase in the project's overall cost. Furthermore, risk events might occur and lead to cost overruns. In the example below, a total of 18 risk events are taken into consideration. To mitigate the effect of these events as well as the uncertainties of cost estimations, a total of 17 corrective measures are introduced to ensure the project finishes within budget with the least possible negative impact. The sub-sections below include a detailed description of all the needed data that are used to run the simulation and achieve the desired results and conclusions.

Construction items and their costs

The construction project analyzed here is comprised of 24 cost elements. Table 1 displays the project items with their three-point cost estimates: the optimistic, most likely and pessimistic one. The three-point estimates of the costs are used to establish a Beta-PERT distributions $f(cost_i; a_i, b_i, c_i)$. The planned project budget (3,077,806 euros) is calculated by finding the total cost of the most-likely figures.

Table 1 Construction Items' costs

ID	Activity description	Costs (Euros)		
		Optimistic	Most-Likely	Pessimistic
1	Financial Close (dummy item)	0	0	0
2	Design	47,250	52,500	60,375
3	General Preparation Works	112,066	120,566	130,000
4	Partioning	427,004	478,375	520,000
5	Flooring	119,383	133,830	141,500
6	Painting	30,000	34,685	54,273
7	Mechanical Installation & Plumbing	731,326	769,848	780,000
8	Electrical Installation	98,752	163,971	180,000
9	Data & Servers Installations	45,000	52,170	80,096
10	Security & Control Installations	66,437	87,071	98,000
11	Fire Safety Installations	51,281	53,798	57,000
12	Audiovisual Installations	10,000	10,800	11,200
13	Joinery	225,000	233,780	259,677
14	Workplace Furniture	106,439	122,205	130,000
15	Meeting Rooms Furniture	110,000	115,500	147,480
16	Other Loose Furniture	125,098	179,400	191,000
17	Greenery & Gardening	22,000	23,024	25,000
18	Curtains & Acoustics	85,000	86,000	89,000
19	Signing & Styling	22,530	37,550	40,000
20	Decorations	7,128	12,016	15,000
21	Consultancy Costs	228,500	228,500	228,500
22	Other Cost Items	65,000	70,000	79,130
23	Reward Value Engineering	10,000	12,217	15,000
24	Project Completion(dummy item)	0	0	0

Risk events

In every construction project, risks occur primarily throughout the execution phase and mainly contribute to uncertainties leading to cost overruns. Table 2 below highlights the main risks the project might face and were retrieved from meetings with two construction managers on site and the project manager overseeing the design and execution. They based their selection of the main risks on the dynamics faced as well as previous experiences with similar type projects. Every risk event has three point cost addition estimate and is associated with a probability of occurrence p_e. Column 6(Affected activities) dictates the activity each risk event impacts with additional costs. For example, for instance, risk event with `ID=3' affects the cost of activity with `ID=6'.

Table 2 Durations, relationships, and probabilities of the identified risk events

ID	Risk event description	Risk cost additions (euros)			Affected activities	p_e
		Min.	Most-Likely	Max.		
1	Mechanical Design Plans rejected.	45,000	50,000	53,000	3	0.25
2	Light reflection of finishes and furniture not in line with BREAM/WELL	11,000	15,000	17,000	15	0.15
3	VOC emissions from materials used too high (Floor finishes and ..)	31,000	40,000	45,000	6	0.15
4	Late delivery of glass and metal elements	38,000	50,000	53,500	19	0.2
5	Unexpected Asbestos	4000	5,000	5,500	7	0.05
6	Covid-19 lockdown (Labour shortage)	10,000	20,000	24,000	25	0.25
7	Labour affected due to market uncertainty and variability.	10,000	20,000	24,000	5	0.2
8	Inaccurate and loss of information due to change in project team over course of project.	14,000	15,000	21,000	4	0.15
9	Dust levels exceeded when works progress with entry of new tenants	2,500	4,500	5,000	8	0.15
10	Failure to reuse existing furniture	4,700	5,000	6,500	17	0.1
11	Change in National Codes (Fire safety regulations).	13,500	15,000	18,000	12	0.05
12	Payments not done in time.	8,000	10,000	12,000	22	0.05
13	Negative Effect of Value Engineering	67,000	75,000	81,000	24	0.15
14	Design Faults	44,000	50,000	57,000	3	0.2
15	Lack of Coordination among different parties/subcontractors	8,200	10,000	11,500	23	0.3
16	Nuisance Levels more strict with new tenants occupying the building	2,400	3,000	3,800	25	0.25
17	Electrical Design Plans rejected	45,000	50,000	53,000	9	0.05
18	Architectural Design rejected.	45,000	50,000	53,000	14	0.05

Mitigation measures on-the-go

In a similar manner to obtaining the risks, mitigation measures were also retrieved throughout the meetings conducted with the construction and project managers. The measures are listed in table 3 along with the three-point cost reduction estimates (minimum, most-likely and maximum possible cost reduction). However, each measure has a negative impact, which in this case is formulated on the basis of multi-criteria effects. Taking into consideration that a project might face several constraints, the negative impacts are divided into three criteria: lost time, noise disturbance and environmental impact. The user input is a rating from 1 to 5 which is a translation based on the scale mentioned in the sections above. For instance, 10 days of lost time translate into a rating of 2/5. Column 9 displays the aggregated average of the negative impact of all three criteria and is considered a projection from the vector space for modelling and computational purposes. The last column highlights the relationship between the measures and the activities. For example, measure with ID=5 affects activity with ID=7 and leads to its cost reduction. It's worthy of notice that each measure can affect more than one activity, yet this is not demonstrated in the specific case above.

Table 3 Mitigation measures' costs, relationships, and negative impacts.

ID	Mitigation description	Mit. Reduction (euros)			Negative Effect				Relations with activities
		Min.	Most-likely	Max.	Lost time	Env.	Noise	Agg.Mean	
1	Engage Client on each design phase	21,500	25000	28,000	4	1	1	37.3	3
2	Re-asses Plans & Install Needed finishes	3,000	5000	6,000	4	1	1	37.3	15
3	Assign Quality Control team for each phase	8,500	10000	14,000	4	1	1	37.3	6
4	Carry on at lower productivity rate	4,000	5000	5,500	4	1	3	59.1	19
5	Monitor Closely each elements on its own and see severity of asbestos	6,000	7000	9,000	5	1	1	50	7
6	Carry on with available teams	5,500	7000	8,000	4	1	2	45.2	25
7	Work with unskilled labour	7,000	10000	14,000	5	1	2	58.1	4
8	Conduct Workshops to make sure information transferred smoothly	7,000	8000	8,750	4	1	1	37.3	4
9	Minimize activities on occupied side of buildings	2,600	3000	4,500	3	2	2	39.4	8
10	Asses furtniture and order only crucial elements not all	1,750	2000	2,500	4	3	2	58.8	17
11	Re-asses plans and installations periodically	4,500	5000	7,000	4	2	1	42.7	12
12	Monitor the quality when cost savings were implemented to make sure its not sacrificed to avoid corrections later	22,000	25000	35,000	1	1	1	5.6	24
13	Engage all teams in design plans and cross check with specifications.	12,000	15000	17,500	5	1	1	50	3
14	Conduct weekly integrated meetings with contractors , subs and all staff.	5,000	7000	8,500	4	2	1	42.7	23
15	Hire drillers by an hourly rate within timetable.	2,500	3000	3,500	3	5	5	81.5	25
16	Engage Client on each design phase	21,500	25000	28,000	4	1	1	37.3	9
17	Engage Client on each design phase	21,500	25000	28,000	4	1	1	37.3	14

Results and benefits of Mitigation Controller

With all the input structured according to the procedures and format displayed in the sections above, the optimization problem was solved using Matlab® R2019b optimization package on a Windows 10 operating system with the following specifications:Intel® Core i5-8250U CPU @1.26GHz, and 8 GB of installed memory (RAM). The elapsed time to find a solution was 7.5 mins for a total number of 5000 iterations with the introduced strict constraints. The latter inputs, results and benefits of the Cost Controller relative to currently adopted tools by the contractor are elaborated in the sections below.

Probability of finishing within budget (S-curves)

After conducting 5,000 iterations, the probability distribution for the cost of the entire project is obtained. The figure below showcases the cumulative probability curves of the project's overall total cost for three cases. The first case or the one represented by the dotted line (No Mit case) demonstrates the total cost by taking into consideration only the stochastic variables in calculating the total cost and without applying any corrective measures. The second case is the other extreme and is the *(Permenant)* case where all mitigation measures are applied within each simulation irrespective if they are needed or not. Such a scenario is considered a conservative one and is proven to be in the coming sections. In fact, the results of this case are the ones obtained in currently available tools like Primavera. The third scenario (*Tentative)* is the outcome of the optimization done in the Cost Controller. The corrective measures in this scenario are only used when needed and within an optimized manner to meet the planned project budget. The main distinction between the third case and the preceding methods is the inclusion of the human goal-oriented behavior where the project manager would only select the most efficient measures that would yield the planned budget with the lease negative impact.

In all three cases, all risk events were taken into consideration and the planned budget is determined by the means of the summation of all deterministic costs of project elements by taking the most-likely costs into account in Table 1.

Figure 2 below depicts all three curves where the probability of each figure could be retrieved by the intersection of the S-curve with the vertical line x=3,077,806. The probability of finishing on budget for the initial case where no measures are considered is about 15%. Such a low probability is due to the inclusion of risk events yielding additional cost uncertainties for each cost element without the use of any mitigation measures that would combat the increase in cost due to uncertainty. When all measures are taken into consideration (dashed line curve) and no constraints are placed on the negative impacts, the probability of finishing on budget rises to around 95%, which is the maximum probability that can be attained within the set budget and available mitigation measures which are not bounded by any maximum negative effects. It's worthy to point out that if the dashed curve does included the constraints on the negative impact, the dashed line would intersect with the solid (MitCC) line at the red circle. Subsequently, if no constraints bound the optimization problem, the MitCC curve would intersect the dashed curves at the 95% probability.

On the other hand, by applying the most optimal set of mitigation measures, the project would finish within budget with a probability of only 70%. The significant difference of probabilities between the permanent and tentative case is due to the stringent constraints of the project. Moreover, the surplus probability comes at a trade-off of the negative impacts of each mitigation strategy as shown in the next section. The user can also use more flexible constraints or a relatively higher budget and still achieve the same probability with much fewer negative impacts and this will also be investigated in the conducted sensitivity analysis.

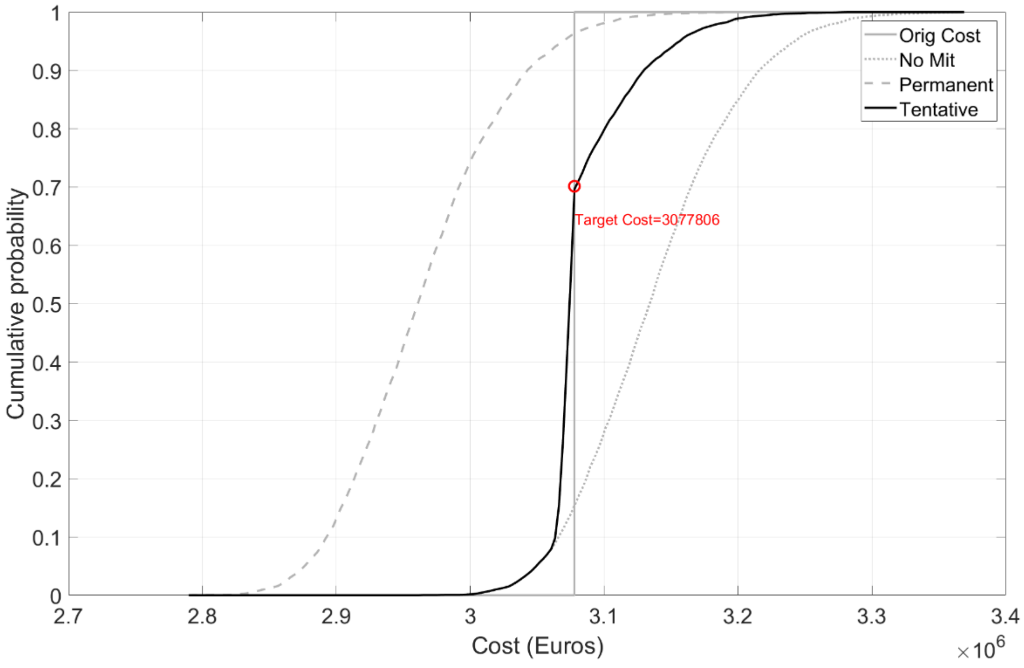


Figure 6 S-curves produced by Monte Carlo simulations

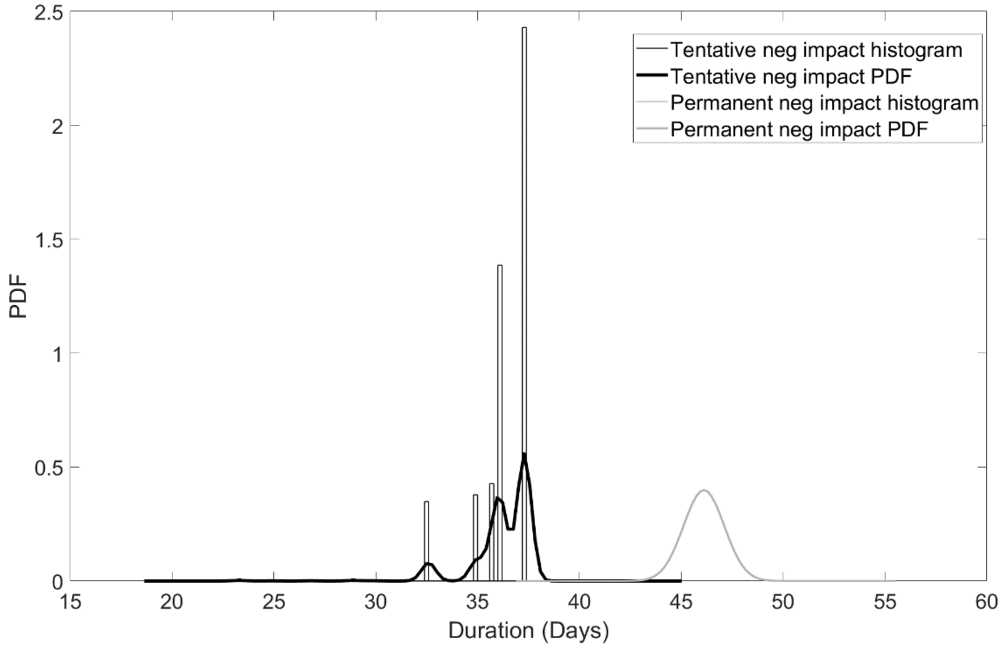
Negative Impact analysis

The main argument regarding developing the Cost Controller is to obtain a more efficient optimization method to select mitigation measures to combat uncertainties in cost estimations of construction projects. It was argued that the traditional way is a conservative one and leads to unwanted additional negative impacts as figure 4 below depicts. The simulation results display those significant unwanted negative impacts can be reduced by adopting the optimal (tentative) mitigation strategy rather than the permanent one. Figure 4 displays the probability density function (pdf) (the figure above) and cumulative distribution function (cdf) (the figure below) for the implementation of both strategies. On the y-axis of the cdf function, the values are not the pertaining probabilities of project completion within budget, but represent the probability of a negative impact occurring when the optimal mitigation strategy resulting from the Monte Carlo simulation is applied.

Before understanding the context of each figure, it's important to under the system's constraints. In the case mentioned above, the user input is the following: planned budget=3,077,806 euros, max total delay=30 points, max total environmental impact= 18 points, max total noise disturbance = 17 points. To put these numbers into context, the summation of individual criteria (ranging from 1till 5 per measure and there are 17 measures under consideration) extend from 17 till 85 which implies the constraints are around their minimum value.

In figure 5, the aggregated average of all criteria used is the metric compared and the highest average impact obtained by adopting the optimal mitigation strategy is 38 whereas the permanent strategy's negative impact is 49. Such insights prove that the traditional approach overestimates the negative impact by 11, which is about a 23% increase and results in an ineffective use of the mitigation measures in place.

In fact, in the real time projects, managers won't select measures at once, but conduct a trial-and-error process to check the effectiveness of different combinations of measures that would yield maximum benefit (closest to planned budget) with the least negative impact. Nevertheless, the main obstacle of this process lies within its manual nature , which might lead managers to overlook certain combinations that would yield substantial savings whether it were time , environmental or noise disturbance benefits.



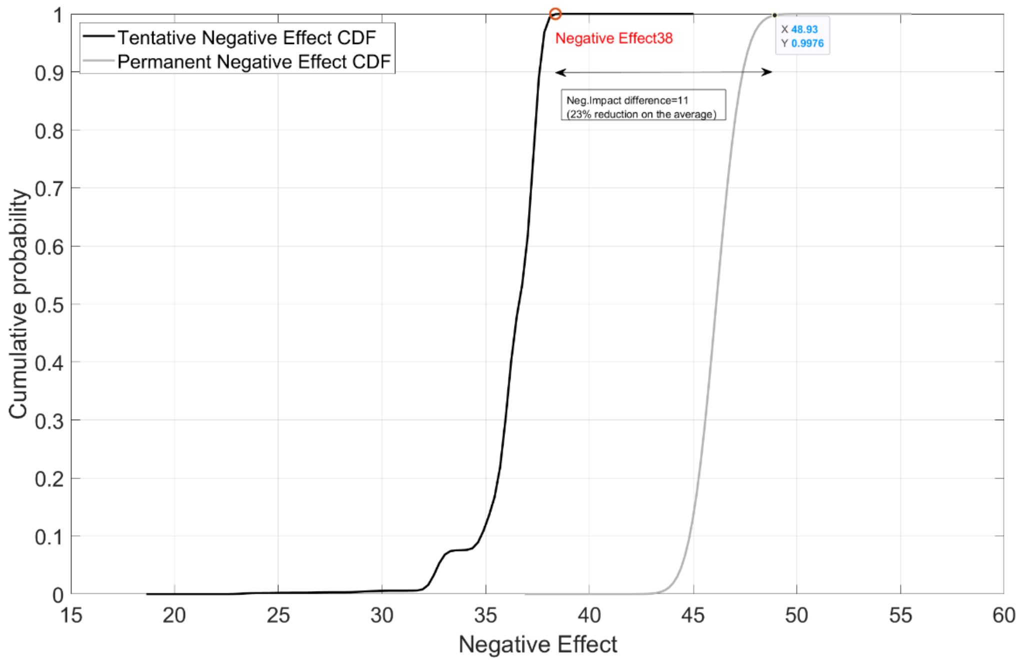


Figure 7 Cost Cumulative Distribution functions of MC simulations for tentative and permanent strategies

Mitigation Measures Selection Frequency

With stochastic analysis, the optimal mitigation strategy is bound to change per Monte Carlo simulation. Hence, in every iteration the chosen measures are stored within a defined metric that can be the called frequency index (FI) which represents the number of times the corrective measure was included in the chosen mitigation strategy. Figure 5 below demonstrates which measures were used identified by their ID(x-axis) and at what percentage were they used out of the the total number of simulations(y-axis). It's worthy to point out that non-selection of measures doesn't mean that they are overall ineffective, but they are ineffective within the set of the system's constraints whether budgeting or negative impacts. For instance, only measures 1, 12 ,16 and 17 were used more frequently and measure 3 at a lesser extent. The other measures remained unused.

Such insights can aid the project manager in prioritizing the choice of mitigation measures. For example, the manager can choose the first 4 mostly used measures and apply them as permanent measures and check for the probability of finishing within budget. If it satisfies the minimum probability requirements needed for the client or him/herself, then this iterative procedure can stop. Nevertheless, it's crucial to apply the measures in a manner of different combinations and avoid using them as a single measure, since the Cost Controller tests the effectiveness of the mitigation strategy rather than the individual measure.

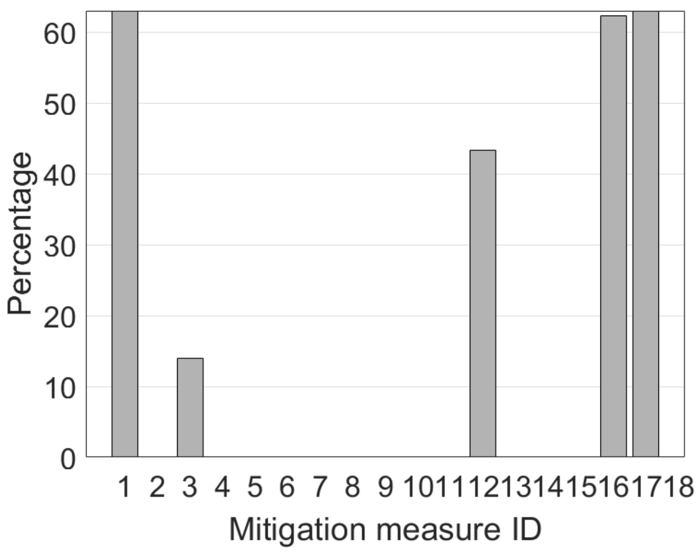


Figure 8 Frequency of Occurrence of each measure per iteration

Sensitivity Analysis

In figure 11 below, four S-curves are demonstrated to test the sensitivity of the tool to constraint changes. Every run is composed of 5000 iterations and demonstrates the cumulative probability of finishing the project within the planned budget. As highlighted previously, each curve contains three scenarios composed of no mitigations scenario, all mitigations and the optimized one obtained by running the optimization function explained above. The key in the following section isn't to compare the scenarios as previously done , but to vary the system's constraints by presenting four different cases and check the variations of probability within the same system mathematical formulation and assumptions.

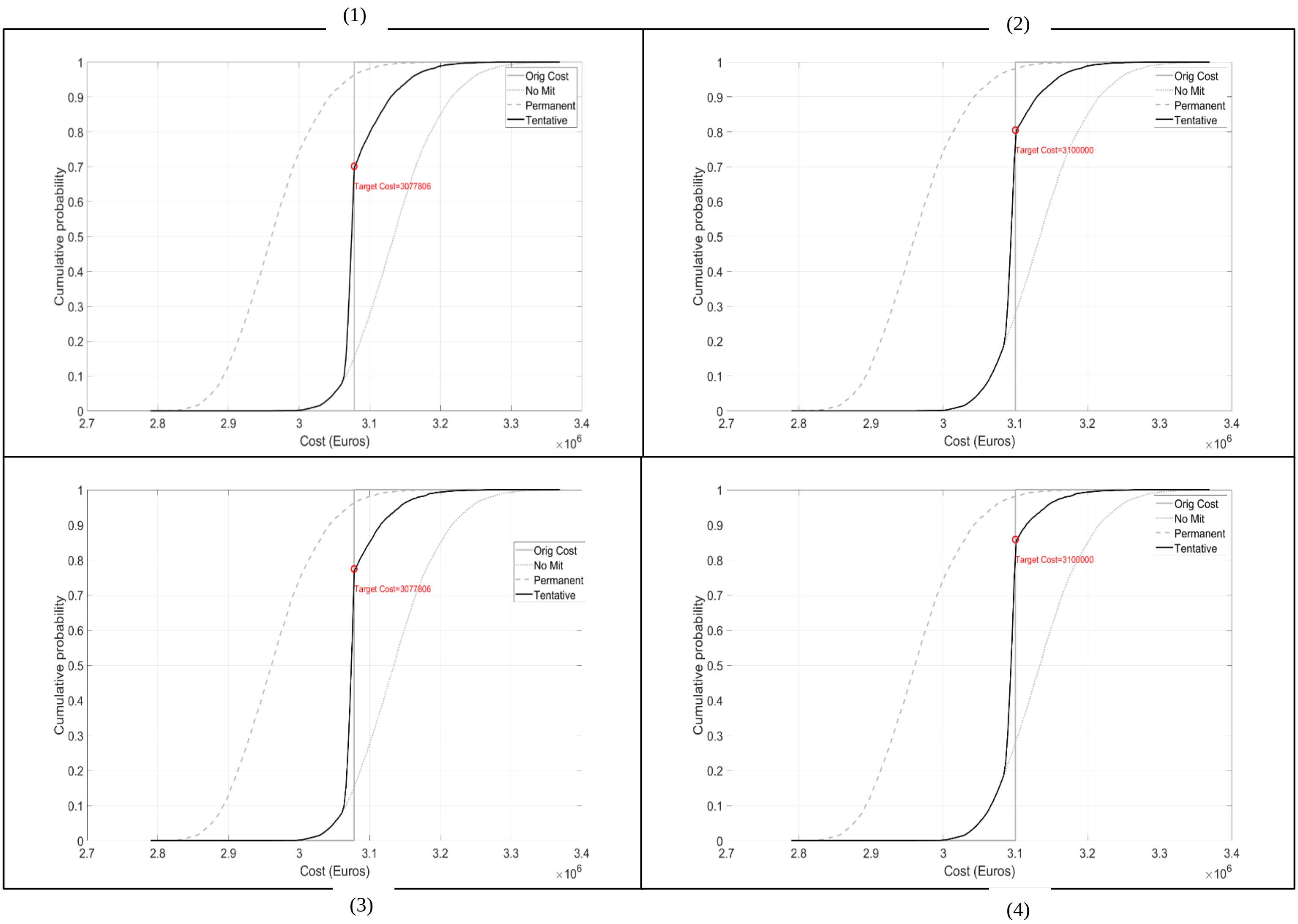


Figure 9 Cumulative Probability of project completion within budget for four cases

Case 1: The project case scenario which was demonstrated in the analysis above and highlights the real planned budget with the specified constraints. Due to the system's strict constraints, the probability of finishing on budget is at 70%.

Case 2: Increased Budget, same constraints: In the second case, the robustness of the tool is tested against increasing the project planned budget and test the variation of probability of finishing within budget with this increase. It has been proven that with only less than 1% increase of the project's budget (in this specific case an increase of 22,200 euros), the probability increases to 80%. The significant increase of 10% can be attained by only relaxing the project's budget. It also displays that the project is running on a very strict cost estimation from the planning team. The practical benefit of demonstrating such analysis could be used at the planning phase during negotiations with the client to assess impacts of increasing the cost of certain elements from the contractor's point of view.

Case 3: Same Budget, Relaxed Constraints: The case at hand assumes the relaxation of negative impacts of applying the mitigation measures. The former can reflect the case of a project where at least one of the negative impacts represented by time delay, noise disturbance and environmental impact is flexible. In the demonstrative example, the project was running on a strict budget, tight schedule and with stringent environmental and disturbance requirements. Therefore, the room to relax one of the constraints wasn't possible. By slightly increasing all three constraints and subsequently increasing the maximum aggregated average of all three, (delay to 47, environmental to 24 and noise to 22), the probability of finishing on budget rises by 10% as well. Such an increase to the optimized strategy with the same risks and measures in place, tests the constraints of the system in place and proves their major effectiveness. Practically, such variations can be argued for during execution phase where the contractor can assess the impacts of reducing constraints with the contractor if the major priority is to finish within budget. The constraints can then be relaxed according to the client's requirements and priorities with relevance to delay or environmental/noise impacts.

Case 4: Increased Budget, relaxed constraints: In the final case, both cases 2 and 3 are combined to test the sensitivity of the tool to changes in the planned budget as well as the client's constraints. Such an approach can be demonstrated in more flexible project requirements. A significant increase to 90%

probability is noticed to finish within budget. In both cases 3 and 4, MitC would now at each run allow for the selection of different combinations due to the relaxation of constraints that might have a bigger cost impact and still lie within the allowed specified flexible negative impact. Such marginal increase in probability is also attributed to the increased in planned budget, thus the impact of risk on affecting the initial project budget is mitigated due the additional buffer added to the project's overall costs.

The key in the section was not only to test the functionality of the tool and the sensitivity of the results with the interchanging the system's constraints, but also to display its various uses. The variation of the results proves that whether during the planning or execution phase, the contractor has the ability to test multiple scenarios and objectively quantify the impacts of project changes on the optimized mitigation strategy as well as the project's planned budget. The latter could also be used in communicating with the client concerning any negotiation or request as well.

The practical scenarios mentioned in each case were also validated with the relevant project managers in the company to ensure that the goal-oriented behavior is included in the modelling and that the scenarios reflect the real dynamics of a construction project.

Validation of Results

After the verification of the Mitigation (Cost) Controller on a real time ongoing project in the illustrative example mentioned previously, it is necessary to validate its usefulness and effectiveness in the practitioner's point of view as well as through a comparison towards the dynamics developing on site. The input data were taken at the beginning of the execution phase which allows carrying the validation in the two methods mentioned: in office with the associated project managers and on site with responsible construction managers.

In terms of the former, three project managers were interviewed and are named: A, B, C. All three project managers highlighted the following when asked about the direct benefits of using the tool:

- The structure of the data input sheets erases any possible discrepancy towards the identification of risks with different stakeholders. In other words, the choice of stochastic cost figures and the quantification of risks' direct impact as well as the corresponding mitigation measures capacity allows for more accurate estimations early in the project planning phase. Such a step can be achieved in currently available tools, yet the added value demonstrated in MitC is incorporating the optimization of the mitigation strategy selection in a more objective organized manner.

- Applying the Mitigation (Cost) Controller throughout the project on an interval basis allows the managers to compare the progress on site with the baseline established by the S-curve of the initial run of the tentative mitigation strategy. In an ideal scenario, the S-curve shouldn't change with the progress of the project. However, with the currently adopted tools the progress observed on site whether time or cost is updated on the input sheet and accordingly the S-curve evolves throughout the project life cycle. Such variability is due to the choice of deterministic figures that don't include possible uncertainties in the cost estimations in the planning phase.
- Through the desk research conducted in the company's offices in the planning phase, it is confirmed that the Mitigation Controller does truly capture the human goal-oriented behavior. All three managers explicitly mentioned that their choice of corrective measures to maintain the budget or time in a project is dependent on a series of trial and error between different measures to find the optimal strategy. In a bigger context, such a method would be inefficient and accordingly the automation of it is very necessary.
- According to the interviewed PM's, the importance of MitC lies not only in decision making but rather in evaluation of project current practices. It contributes to the enhancement of communication with all stakeholders at two levels: Inter-Organizational approach (external with client) to evaluate effect of certain changes and their effects on the optimal chosen mitigation strategy like postponing some works. The communication is also enhanced internally in planning phase which would influence data driven decision making.

With relevance to the direct comparison on developments on site the following is noted:

- Four weeks into the project, 3 risks (ID=4,6,14) fired and led to a significant drop in the manager's probability to finish within budget in their own planning due to the negligence of uncertainties in the cost estimation process.
- Two of the suggested mitigation measures were actually implemented on site by the construction managers to increase probability of success and mitigate the impact of the fired risks.

Such observations don't only reflect the accuracy of modelling and automation of selecting the corrective measures in the Cost Controller, but also reflect the goal-oriented behavior of project managers to finish within budget. The Cost Controller and within the limited scope of the project that it was implemented on was able to partially reflect reality on site and in office.

The following section sheds light on the drawn-up conclusions regarding the Cost controller as well as its limitations and areas of further development.

Further Enahancements

The current version of the Mitigation (Cost) Controller contains certain limitations that should be addressed to establish an even more accurate representation of project dynamics. Potential future improvements that would enhance the modelling and applications of the Mitigation (Cost) Controller are listed below:

- In one of its negative impact criteria, the Mitigaiton (Cost) Controller evaluates lost time in a project as a possible trade-off to maintain cost. The modelling of lost time doens't differentiate whether the time lost is on the critical path and thus can be considered a delay or its the float on a non-critical path. Incorporating network planning to the cost controller allows a more accurate representation of the lost time and gives managers a clearer vision on the trade-off they are accpeting.
- The stochastic variables are defined using PERT distriutions. Further developments allow the exploration of different distributions that might be more accurate than the currently adopted one.
- Introduce reward schemes like clauses included in design and build contracts or cost plus contracts where the client and the contractor split the difference between the project's overall cost and the guaranteed maximum price (GMP) , if agreed upon , given that the latter is greater than the former. Such a step would now drive the search for an optimal mitigation strategy that would go below the planned budget.

Conclusion

Traditional approaches in probabilistic cost estimations for construction projects include a major modelling error. Current available tools and research overlook a major factor: the project manager's goal-oriented behavior of establishing the maximum benefit with the least negative impact. Accordingly, the cost controller was developed to capture this factor and automate it. Furthermore, the cost controller offers practitioners the chance to include multi-criteria assessment in their analysis towards finding optimal mitigation strategies that would combat the uncertainties arising at the construction site as well as the extensive requirements set by their clients. Such a novel step also allows for a more accurate representation of construction complexities and stretches the horizon beyond the traditional cost-time tradeoff and includes environmental impact as well as noise disturbance and models the choice of optimal mitigation strategies as such.

The Cost Controller as a product combines three point stochastic variables for cost elements, project risks and mitigation measures 'capacities with Monte Carlo simulations to generate the cumulative probability curve (commonly known as the S-curve) of within budget project completion. Such a modelling structure allows for the minimization of uncertainties with respect to the estimations done before the execution phase and allows for more accurate representation of project dynamics.

In comparison to classical planning methods, the cost controller not only is more effective in establishing a more effective strategy, but also allows for more dynamic project planning. Project managers can set different objectives for each project. For instance, if the project is sustainability focused, the constraints related to environmental impact can be set to minimum and would allow managers to have the flexibility to choose among different trade-offs. In all cases, the cost controller chooses only the most effective corrective measures that satisfy the maximum effectiveness per selected strategy.

To sum up, with the development of such a tool , project managers currently have a functional model that would support their decision making in a more pragmatic approach that reflects their goals and mimics their behavior and approach in maintaining the highest probability of preventing construction project cost escalations.

Data Availability Statement

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Chapter III: Personal Reflection

Overall Conclusions

The Cost Controller as a product combines three point stochastic variables for cost elements, project risks and mitigation measures ‘capacities with Monte Carlo simulations to generate the cumulative probability curve(commonly known as the S-curve) of within budget project completion. Such a modelling structure allows for the minimization of uncertainties with respect to the estimations done before the execution phase and allows for more accurate representation of project dynamics.

In comparison to classical planning methods, the cost controller not only is more effective in establishing a more effective strategy, but also allows for more dynamic project planning. Project managers can set different objectives for each project. For instance, if the project is sustainability focused, the constraints related to environmental impact can be set to minimum and would allow managers to have the flexibility to choose among different trade-offs. In all cases, the cost controller chooses only the most effective corrective measures that satisfy the maximum effectiveness per selected strategy.

To sum up, with the development of such a tool , project managers currently have a functional model that would support their decision making in a more pragmatic approach that reflects their goals and mimics their behavior and approach in maintaining the highest probability of preventing construction project cost escalations.

Personal Reflection

As a final note, I would like to reflect back on this challenging, yet exciting journey.

Over the past months, I was working with ambition and motivation on the topic at hand, mainly for 2 reasons: First, I am grateful for the opportunity to work on the development study at hand with a group of professors who share the same passion for my topic and who also enjoy engaging in open discussion that would stimulate thinking and try to make a difference and leave an impact.

A second reason that incentivized me to work with passion on this assignment was the high interest of the people at Drees&Sommer in the topic. When introducing the topic, the common reaction was: “That’s very interesting, why we don’t do it actually?”. Throughout this report, I tried to answer this question constantly, and my final answer to all practitioners who wants to achieve more successful results in their projects: There is no reason. Just do it.

I learned many lessons during this journey, here are the most important ones:

- Every problem encountered can be solved by proper planning and having the right proactive measures in place.
- In a similar manner of the model, a person must specific a goal they need to achieve and work backwards from it. That’s the only an individual can ensure that no intermediate steps are missing and can work even further and with more eagerness towards their goal. That’s the exact same mental model I followed when conducting this research and made sure I want to finish it on time.

Now, looking at the outcome of my research, I can proudly claim that I am pleased with the obtained results given all the ambitious plans and deadlines that I imposed on myself. If I had more time, I would try and include one of the main limitations of the development and is to call TETRA software into MATLAB on the run and observe if any outcomes differ.

Lastly, I would say that, if there is to be a future for Mitigation Cost Controller, it should be seen as normal routine practice and not as something special or unusual. I’ve spent the past pages talking about how to apply the tool and believe now is the chance to leverage such an opportunity and implement it in planning and execution of construction projects.

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Erratum

At the moment this document was written, as per the latest version on the 12th of February 2022, a minor modelling error was observed regarding the manner of the quantification of the aggregated average of each mitigation measure. The calculations made on TETRA were static and only included the aggregated average as an input from the excel sheet. To have a more accurate representaiton of the results, it’s necessary to create a link that would be included in the model and calculates the aggregated average on the go per iteration when needed by introducing the backend calculations TETRA carries out or by calling off TETRA into matlab when needed within the Monte Carlo Simulation. In this manner, instead of finding the mean of the aggregated values in one mitigation combination , the modelling error is eliminated by finding the aggregated average of the aggregated values per iteration and per comnbination. The latter step is going to be modified by introducing a series of optimization functions to accomodate the link to TETRA which would contain a table with an automated upfront calculations of aggregated average negative impact of all possible combinations of mitigation measures.

Appendix

All calculations made on TETRA and constituted column 16 of the input spreadsheet are based on calculations and ratings inputted on TETRA software and are displayed in the figures below.

Tetra Solution Report

Model: Mit1
By: Default User
Date: Mon Jan 17 14:52:12 2022
Weight Paradigm: n/a
Parent Criterion: Criteria

Overall Ratings

Rank	Alternative	Rating
9	M01	37.345
9	M02	37.345
9	M03	37.345
2	M04	59.101
5	M05	50.000
6	M06	45.237
4	M07	58.139
9	M08	37.345
8	M09	39.445
3	M10	58.784
7	M11	42.699
10	M12	5.606
5	M13	50.000
7	M14	42.699
1	**M15**	**81.492**

Criteria Weights

Criterion	Local Weights	Global Weights	Weighting Values
Criteria			
Delay	0.500	0.500	50.000
Enviornment	0.200	0.200	20.000
Noise Levels	0.300	0.300	30.000

Figure 10 Final aggregated average of negative impacts obtained from TETRA for each measure as well as criteria weights as specified by client.

Ratings

Criteria\Delay

	Default User:Ratings
M01	80.000
M02	80.000
M03	80.000
M04	80.000
M05	100.000
M06	80.000
M07	100.000
M08	80.000
M09	60.000
M10	80.000
M11	80.000
M12	0.000
M13	100.000
M14	80.000
M15	60.000
M16	80.000
M17	80.000

Criteria\Enviornment

	Default User:Ratings
M01	0.000
M02	0.000
M03	0.000
M04	0.000
M05	0.000
M06	0.000
M07	0.000
M08	0.000
M09	20.000
M10	60.000
M11	20.000
M12	0.000
M13	0.000
M14	20.000
M15	100.000
M16	0.000
M17	0.000

Criteria\Noise Levels

	Default User:Ratings
M01	0.000
M02	0.000
M03	0.000
M04	60.000
M05	0.000
M06	20.000
M07	20.000
M08	0.000
M09	20.000
M10	20.000
M11	0.000
M12	20.000
M13	0.000
M14	0.000
M15	100.000
M16	0.000
M17	0.000

Figure 11 Individual ratings for each measure per criteria