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MASTER THESIS
2019

A COMPARISON
OF RISK
ANALYSIS
APPROACHES
PERFORMANCE
ASSESSMENT OF COST
AND TIME ESTIMATING
ON A REAL PROJECT

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PERFORMANCE ASSESSMENT OF COST AND TIME ESTIMATING ON A REAL PROJECT

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Graduation thesis

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Faculty: Civil Engineering and Geosciences (CiTG)
Master track: Construction Management and Engineering (CME)
Course(s): CME 2001 Master Thesis Preparation, CME 2000 Master Thesis

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PREFACE

This report is the product of my thesis research, the final step in attaining the Master of Science degree for the Construction Management and Engineering programme at Delft University of Technology.

Thesis is the most intense and rigorous part of the master programme, and it is therefore essential that the topic of research is interesting to the researcher. For that reason, I pursued a research on the area of risk management. Being a proactive and methodical individual, I was always intrigued by the concept of risk management, but generally had a very abstract understanding of it. Early in this master I developed a deeper comprehension on the subject and appreciated the importance of good risk management for the success of projects. The more I learned the greater my interest. I found the method of probabilistic analysis especially intriguing and decided that a thesis on that topic would be fitting for me.

Fast forward, after 8 months of actively working on thesis I am writing this preface. The journey to this point was full of educating and enlightening experiences that contributed to my personal development as an engineer and manager. I acquired valuable insights on the practices of risk management and the specifics of probabilistic analyses. This journey would be poorer, even impossible without the support of my university committee members and of FLUOR BV managers. Therefore, I would like to thank you Hans, Erfan, Rob, Nishikant and Arne for your guidance, insights and dedication whenever required. Finally, I would like to thank my parents for their trust and selfless support that got me so far in life and my friends for their company that kept me motivated and upbeat throughout thesis.

Demetris Zachariou
Delft, January 2019

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EXECUTIVE SUMMARY

Risk management is undoubtedly a precious component of the overall project management field. It assists in identifying, assessing and mitigating the uncertainties that are present in a project. These uncertainties affect important measures of a project, of which cost and schedule are the most prominent, and consequently put project success under pressure. Risk analysis, especially in its quantitative form, is a core process of risk management that provides valuable insights regarding these uncertainties.

Numerous different procedures for quantitative risk analysis exist, but generally, they can be classified in two types based on the way they treat the cost and schedule components of a project. The one type is the separated approach (SA). That is, two risk analyses are performed, one for schedule and one for cost, which are independent of each other. The other type is the integrated approach (IA). In this approach one risk analysis is performed, where schedule and cost components are simultaneously analyzed, and are no longer independent of each other.

The advantages and disadvantages for each approach are well described in literature. However, there is little empirical evidence of the performance of different approaches when they are applied on real projects. For example, it is widely agreed that cost and schedule variables are related to each other and therefore, the integrated approach is regarded as the most accurate one to perform a risk analysis. Empirical evidence supporting this statement is however scarce. Not a lot of research is conducted to investigate the actual performance of different risk analyses on real projects. This is an important gap in literature that has implications extending to the industry.

The goal of this research is therefore to compare the outcomes of different approaches when they are implemented on a real project, against the actual outcomes of the project to get an indication of the relative performance of each approach. Particularly, the Proposed Separate Approach P'SA, the Proposed Integrated Approach P'IA and the Company's Separated Approach C'SA are applied on a completed project and their outcomes regarding cost and schedule are compared to each other and to the actual project outcomes.

The main research question is formulated as follows:

To what extent do the outcomes of the C'SA, P'SA and P'IA differ from each other and which approach is more accurate?

To answer this question and accomplish the goal of this research, a research approach is set. First a good understanding of risk analysis in general must be developed. This is achieved through desk research. A combination of extensive literature study and critical thinking lead to the development of the P'SA and P'IA. Through the research it is recognized that risk management is a very dynamic field with no clear nomenclature. Multiple definitions and therefore multiple interpretations exist for the same terms. This results in confusion among academics and practice individuals. An effort is made to explain and unambiguously define the concepts and terms that will be used throughout the report.

Also, while it is recognized that there are multiple uncertainty types, there is no commonly agreed classification of these types. For this research a classification of uncertainties is adopted that includes the following three types of uncertainty, regarded as the most important: risk events, inherent variability and correlation. These types are included in the P'SA and P'IA.

The P'SA includes two separate risk analyses, the Proposed Cost Risk Analysis (P'CRA) and the Proposed Schedule Risk Analysis (P'SRA). The P'IA includes only one risk analysis, the Proposed Integrated Cost

and Schedule Risk Analysis (P'ICSRA). The Monte Carlo method is used in all analyses to perform probabilistic analysis.

The company's practice for risk analysis is investigated by performing a case study research and examining the procedure followed on a real project. It was identified that the company followed a version of SA, although quite different from the P'SA. Specifically, the C'SA included three separate risk analyses, two about cost (C'CRA-1 and C'CRA-2) and one about schedule (C'SRA). The analyses differ substantially from the proposed ones. Notably they do not include all three uncertainty types as shown in the following table.

		Cost uncertainty elements			Schedule uncertainty elements		
		Inherent variability	Risk events	Correlation	Inherent variability	Risk events	Correlation
C'SA	C'CRA-1	—	+	—	—	—	—
	C'CRA-2	+	—	—	—	—	—
	C'SRA	—	—	—	—	+	—
P'SA	P'CRA	+	+	+	—	—	—
	P'SRA	—	—	—	+	+	+
P'IA	P'ICSRA	+	+	+	+	+	+

Next, the P'SA and P'IA are implemented on the same real project and their outcomes are generated. The available outcomes from each analysis are presented in the following table.

		Outcomes					
		Cost contingency	Schedule contingency	Cost risk events ranking	Schedule risk events ranking	Joint confidence level	Probabilistic cash flow
C'SA	C'CRA-1	+	—	—	—	—	—
	C'CRA-2	+	—	—	—	—	—
	C'SRA	—	+	—	—	—	—
P'SA	P'CRA	+	—	+	—	—	—
	P'SRA	—	+	—	+	—	—
P'IA	P'ICSRA	+	+	+	+	+	+

All approaches' outcomes are then compared against each other and against the actual project outcomes. To make the comparison more robust, the final project cost and schedule results are further analyzed. Specifically, any cost and schedule developments during the project are classified to either contingency related or change orders related. The contingency related part is then compared to the results from the approaches.

Based on this comparison, a conclusion is drawn, and an answer is given to the research question. Regarding cost contingency estimation, the P'IA fared better with a contingency estimation short of the

actual cost contingency consumption by 3€ million, followed by the P'SA with a 23€ million difference and the C'SA last with a 36€ million difference. Regarding schedule contingency estimation the C'SA performed better with a schedule contingency estimation 10 days over the actual schedule contingency consumption, followed by the P'SA and P'IA with a difference of 45 days. The P'IA provided the capability to produce outcomes unattainable from the C'SA and P'SA that can be utilized to improve the management of a project.

For a robust conclusion that can be generalized, a bigger sample is required. The results are highly affected by the specificities of the project and therefore a concrete conclusion cannot be drawn from a small project population, let alone from a single project. This consists the biggest limitation of this research.

Finally, the experience during the research triggered a discussion on several topics. The following statements give a general idea:

- The type of contract that is used in a project, reimbursable or lump sum, determine which side, contractor or client, has the most risk and consequently the most eagerness for a proper and accurate risk analysis.
- The impacts from scope changes vastly exceed the contingency estimates. The identified approaches cannot confront this fact and there is no simple solution.
- The implementation of the integrated approach in an environment optimized for the separated approach is more labor intensive and effortful. A supportive environment may reverse this however.

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LIST OF ABBREVIATIONS

SA	-----	Separated Approach
IA	-----	Integrated Approach
SRA	-----	Schedule Risk Analysis
CRA	-----	Cost Risk Analysis
ICSRA	-----	Integrated Cost-and Schedule Risk Analysis
TI	-----	Time Independent
TD	-----	Time Dependent
CPM	-----	Critical Path Method
MC	-----	Monte Carlo

Prefixes

C'	-----	Company's
P'	-----	Proposed

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1 INTRODUCTION

In this introductory chapter the research design is presented. First, the scene is set by describing the environment surrounding the research subject. By carefully examining the literature, a problem is identified that triggers the need for research. In line with the problem, the goal of the research is established along with a set of research (sub) questions. The approach to tackle the research is then explained and a research framework is shown. Last, the outline followed in this report is presented.

1.1 SETTING THE SCENE

Every project is a unique, one-time and temporary undertaking, with predefined goals that must be accomplished within predefined constraints to be regarded as successful (Benta, Podean, & Mircean, 2011). Because of their unique nature, projects are in principle full of uncertainties. Construction projects are not an exception. Contrary, because of factors like numerous stakeholders, uncontrolled environment, high complexity, they are exposed to even greater uncertainty (Harishkumar & Pravin, 2016; Isidore, Back, & Fry, 2001; Olawale & Sun, 2015; Senesi, Javernick-Will, & Molenaar, 2015). In this unfamiliar environment, where assumptions and estimations are necessary, uncertainty is inevitable and project success is not certain (Nicholas & Steyn, 2017).

Project success has several interpretations depending upon the viewpoint of each stakeholder (Ogunlana, 2010). Lim and Mohamed (1999) identify two perspectives: macro-level success and micro-level success. Macro-level success is more concerned with the whole life cycle of a project, including the operation phase. Micro-level success assesses a project based on the execution performance. Client parties have an interest to adopt the macro-level approach, while contractor parties would be more concerned about the micro-level approach.

In literature and practice, micro-level approach, even if not explicitly referred as such, is given the most attention. In this approach, success of a project is widely attributed to the performance of the iron triangle elements: Cost, Time and Quality. These success criteria are strongly embedded in the project management practice for years and included in many project management definitions (Atkinson, 1999). Sustainability, safety, or other factors can also be considered as project objectives but in literature usually they are not investigated in a quantitative way (Willems & Vanhoucke, 2015). Following from that, it makes sense to measure the performance of projects on the outcomes regarding the iron triangle success criteria. However, because of the difficulty of quantifying and objectively measuring, quality is also usually excluded from research and practice, and projects are assessed quantitatively mainly on their cost and time results (Habibi, Kermanshachi, & Safapour, 2018; Willems & Vanhoucke, 2015). This assessment takes the form of a comparison of the initially estimated figures of the two measures against the realized ones. A project would be regarded as successful if it is completed within the estimated time and budget, or close to those values¹ (Ika, 2009).

It becomes apparent that success of a project is heavily dependent on the accuracy of the estimates performed at the beginning of the project, and on the management of the project during execution so that it is guided towards the desired end (Olawale & Sun, 2015). Therefore, engineers and managers strive to make accurate and precise forecasts, before or early in the project, about the outcomes of the project. On the same line, they monitor the performance of the project and try to control and manage it so that it does not deviate substantially from the targets that were set during estimations. Despite all

¹ According to experts, a project can be regarded as successful when total cost and duration deviate less than 10% from the estimates.

efforts from the parties involved in projects to deliver projects that meet the time and cost objectives, the norm is to have a substantial difference between the estimates and the actual project outcomes. As a rule, projects suffer from cost and schedule overruns (Fister Gale, 2011; Flyvbjerg, Holm, & Buhl, 2002; Ika, 2009). There are several reasons contributing to this phenomenon. According to Nicholas and Steyn (2017), “Uncertainty and lack of accurate information” is an important one.

The estimates for time and cost are first produced in the very early stages of the project, during the planning phase. Only limited information is available then and estimates are mostly based on judgement and past experiences from similar projects. Consequently, the estimates at that point of time tend to be very rough and unreliable. Obviously, the less defined the project, the less educated the estimates, and the higher the chance that the actual project results will deviate from the estimates. As the project progresses, more information becomes available and the cost and time estimates are revised accordingly (Nicholas & Steyn, 2017). Even though the estimates will be improving in every iteration, they will never be completely accurate. They will always be subjected to incomplete data and uncertainties, until the project is completed (Vrijling, 2009). Proper risk management is vital to effectively identify the uncertainties and develop suitable responses to deal with their consequences.

Contingency reserve is an amount usually added to cost and schedule estimates, to compensate for uncertainty (Chapman & Ward, 2003; Kwak & Ingall, 2009; Mak & Picken, 2000; Nicholas & Steyn, 2017; PMI, 2017; Senesi et al., 2015; Sonmez, Ergin, & Birgonul, 2007). The contingency reserve may be a percentage of the estimated cost or duration, a fixed number, or may be developed by using quantitative risk analysis techniques (PMI, 2017). In principle, this contingency amount should be proportionate to the level of uncertainty that the project is subjected to. The higher the uncertainty regarding costs or schedule, the bigger the contingency amount that should be accounted for cost or schedule. The contingency is then added to the original, raw estimates to form the cost and schedule baselines. The baselines then serve as the reference against which the progress and performance of the project is measured, so that appropriate actions can be taken.

The importance of correctly estimating contingency, to consequently create a sound and realistic baseline, is undeniable. For example, a cost contingency estimated too low can potentially lead to considerable financial losses for the contractor. If it is set too high, it will reduce the chances of winning a contract. Still, in the construction industry limited attention is paid to this aspect. In extreme cases uncertainty is completely disregarded and no contingency is accounted for. In such cases, cost and schedule baselines are composed from just the raw, point estimates. This would be cost and time management at its most basic form, using a clearly deterministic procedure and lacking any appreciation of uncertainty.

As mentioned, one method is to add a predetermined percentage of contingency to cost and schedule estimates (Mak & Picken, 2000; Senesi et al., 2015; Sonmez et al., 2007). The percentage to be used is determined by expert judgement based on past experiences and from the outcomes of a qualitative risk analysis. However, since the outcomes are of qualitative nature, interpretation will be needed to gain an indication. Also, expert judgement outcomes depend heavily on the competence of the expert. As a result, the percentage selected cannot be adequately reasoned, the contingency amount can be unrealistic and the various contributors to uncertainty cannot be identified nor quantified (Harishkumar & Pravin, 2016; Mak & Picken, 2000).

A more structured approach is to perform a quantitative risk analysis. In this approach, probabilistic estimating techniques are utilized to perform a more advanced and complete analysis of a project. These techniques enable the calculation of contingency reserves and risk event rankings in a more transparent and accurate manner among other useful risk management information (Sander, Moergeli,

& John, 2016). Some statistical techniques are sensitivity analysis, expected monetary value analysis, decision trees, or simulations (Shannon, 2015). Monte Carlo (MC) is a well-known simulation technique that is used in project management. This method produces a distribution function for the total project cost or duration by iteratively calculating the results for stochastic cost or schedule models.

Depending on the company's risk tolerance, an appropriate confidence level is selected, and the corresponding contingency can be extracted from the distribution. The confidence level indicates the probability of not exceeding a specific value. For example, when an 85% confidence level is desired, then a value for cost or time should be selected from the corresponding distributions for which an 85% probability of not being exceeded exists. A risk averse company will select high confidence levels while a risk taker will select lower ones. The procedure of selecting a contingency amount through quantitative risk analysis is in theory more accurate and substantiated than the alternatives mentioned before.

MC simulation analysis also provides the capability to create a prioritized list of quantified risk events. Because of the quantitative nature of the analysis, the effect that each risk event has on the project cost or schedule is explicitly calculated. It is then possible to rank the risk events according to the severity of their impact on the cost or duration values. This prioritized list of risk events provides the opportunity to project managers to focus their attention on the events that are significant, where mitigations can lead to better project outcomes (PMI, 2017).

Two main approaches can be distinguished regarding the way the quantitative risk analysis on cost and schedule is performed. The one is the Separated Approach (SA). As the name suggests, in the SA cost and schedule are treated independently of each other. That means two separate risk analyses are performed, the Cost Risk Analysis (CRA) and the Schedule Risk Analysis (SRA). On the other hand, there is the Integrated Approach (IA). In the IA, cost and schedule are not independent of each other anymore. One way to replicate their relation is by inserting the two type variables into one model and considering the one as a function of the other. Using this model, a single Integrated Cost and Schedule Risk Analysis (ICSRA) is performed.

It is generally accepted that total project costs are affected by duration variation (Isidore & Back, 2002; Mawlana & Hammad, 2015). A longer project duration will in principle consume more work hours which bring extra costs. In the IA this relation is respected and replicated by considering cost components as a function of time whenever necessary. Therefore, the main differentiator from the SA is that uncertainty introduced to schedule will have an impact on associated cost components as well.

1.2 IDENTIFYING THE PROBLEM

The aforementioned quantitative risk analysis approaches are well documented and described in literature. Various alterations of the approaches are proposed, and their benefits and drawbacks are extensively examined from a theoretical perspective. However, theoretical analysis is one thing and actual practical implementation of a risk analysis approach on a real project is another. The latter is not given the same attention in literature and therefore there is little information on how the approaches are implemented in practice and on how they perform.

As a result, there are several unanswered questions about the implementation of the IA in practice and about its relative performance compared to SA. For example, the theoretical advantages of the IA over the SA are thoroughly analyzed in literature (Hulett & Avalon, 2017; Hulett et al., 2011; Shannon, 2015; Xu, Yu, & Li, 2014). In theory the IA should produce more correct and representative distributions and risk event rankings regarding project costs. However, there is little to no evidence that this is the case

in practice. Also, there is little information on whether the quantitative risk analysis procedures applied by the industry are the same as the ones found in literature and whether they perform better.

Consequently, a research on the implementation and performance of quantitative risk analyses in real project environments is imperative to bridge the gap in literature, advance the knowledge on the subject and exploit the potential benefits in practice.

1.3 RESEARCH GOAL

The goal of this research is to compare the outcomes of different approaches when they are implemented on a real project, against the actual outcomes of the project to get an indication of the relative performance of each approach. Particularly, the Proposed Separate Approach P'SA, the Proposed Integrated Approach P'IA and the Company's Separated Approach C'SA are applied on a completed project and their outcomes regarding cost and schedule are compared to each other and to the actual project outcomes.

1.4 RESEARCH QUESTIONS

Based on the identified problem and the formulation of the research goal, the following main research question and the supportive sub questions are devised:

Main research question:

R.Q. To what extent do the outcomes of the C'SA, P'SA and P'IA differ from each other and which approach is more accurate?

Research sub-questions:

1. *What are the procedures for the P'SA and for the P'IA?*
2. *What is the procedure for the C'SA as implemented on the case study project and what outcomes were produced?*
3. *What outcomes are produced when the P'SA and P'IA are performed on the case study project?*
4. *What are the actual outcomes of the case study project?*

1.5 RESEARCH FRAMEWORK

To answer the main research question, a suitable approach that follows the structure of the sub-questions is developed. Through methodical steps, the required knowledge is gradually developed to the point that an answer can be given to the main question. A description of the approach follows, and the research framework is illustrated in Figure 1.

1. *What are the procedures for the P'SA and for the P'IA?*

In order to correctly implement the two approaches and produce reliable outcomes for further investigation, first a good understanding of the procedures behind the two approaches must be developed. This is done through desk research where literature is extensively studied (Verschuren, Doorewaard, & Mellion, 2010). All concepts that are considered relevant to the research are confronted, from broad notions to specific details. Imperative is the decomposition of uncertainty into its elements to simulate it correctly in the models. Of course, a plethora of procedures can be identified and can be created. The proposed procedures in this study are the product of extensive research and are based on procedures and guidelines found in the recommended practices published by AACE (Caddell et al., 2012; Hollmann et al., 2008; Hulett et al., 2011; Humphries, 2009)

2. *What is the procedure for the C'SA as implemented on the case study project and what outcomes were produced?*

Moving forward, the risk analysis procedure as implemented in practice during a project, needs to be identified. To acquire a deep insight for the current practice, the case study research method was considered to be the most fitting strategy (Verschuren et al., 2010). Particularly, a project from the organization is selected that complies with certain selection criteria. It is known in advance that the specific organization is implementing a version of the SA for quantitative risk analysis on its projects. Since the procedure is already implemented, the results on its outcomes will be retrieved for the later evaluation. Importantly, all the data and information used in the C'SA will be collected to be reused as inputs for the P'SA and P'IA.

3. *What outcomes are produced when the P'SA and P'IA are performed on the case study project?*

With the procedures of the P'SA and P'IA identified and with all the required project information retrieved and ready to be used as inputs, the investigation can take place. It is expected that for some inputs required for the P'SA and P'IA there will be no information available from the case study project since the C'SA differs. In such cases, the necessary data for the inputs is taken from literature or expert's opinions. After the implementation of the two approaches on the case study project, the respective outcomes will be generated and become available for further investigation.

4. *What are the actual outcomes of the case study project?*

By this step, the results from the P'SA and P'IA and from the C'SA are gathered. For some of these outcomes, respective actual project results are available. These results will be used as a reference to assess the results on respective outcomes from the analyses. Specifically, total project cost and duration data from project documentation is retrieved. This step is intentionally performed after the implementation of the P'SA and P'IA because knowing the outcomes of the project would have provided the benefit of the hindsight. With this knowledge, the implementation of the P'SA and P'IA might have been performed in a biased way.

R.Q. To what extent do the outcomes of the C'SA, P'SA and P'IA differ from each other and which approach is more accurate?

Finally, all information is available to tackle the final step. The results from the C'SA, the P'SA, the P'IA and the actual project outcomes are compared to each other. The outcomes of the comparison provide valuable insights on the effectiveness and accuracy of each approach. A conclusion can be reached on the relative performance of each approach for that specific project. A generalization of the conclusion is not possible due to the small sample but a contribution to the knowledge concerning the specific subject will be achieved.

1.5.1 DATA COLLECTION

Although data collection sounds like a simple task, it proved to be one of the most painstaking and resource intensive tasks of this research. The nature of the research demanded the collection of a large amount of data. Because this research is conducted two years after the case study project completion, the required data were not readily available. All data was archived and stored in the organization's servers. As a result, no individual could provide specific data at request. The only way was to get access to the project folders, examine the whole directory, filter the relevant data necessary for the research, and collect them.

Apart from the large size, the required data was originally created from several teams within the organization. Cost, schedule and risk are some of the categories for which information was needed. As a result, many data file types were confronted for which different software solutions were necessary to be extracted and observed. Specifically, the following software packages were essential to retrieve and utilize the data:

- Oracle's Primavera P6 Professional 17
- Oracle's Primavera Risk Analysis
- Palisade's @Risk
- Microsoft's Office
- Custom Organization's software

While reusing the same data from the case study project was the priority, experts and literature were consulted when that was unfeasible.

1.6 REPORT OUTLINE

Following the introductory chapter of this report, the second chapter presents the theoretical framework of the research. Concepts and notions are examined and unambiguously interpreted and the procedures for the P'SA and P'IA are developed. By using a sample project, a walkthrough is presented for P'SA and P'IA to assist in better understanding of the procedures. The third chapter investigates the case study project and reveals the exact procedures for C'SA. Special considerations regarding the application of the P'SA and P'IA on the case study project are explained. The fourth chapter presents the results from all the analyses, while the fifth chapter attempts an analysis on these results. In chapter six, a discussion on several key matters surrounding the research and the results is carried out. Last, chapter seven draws conclusion on the research and effectively provides an answer to the main research question. In the same chapter the potential limitations are mentioned, and recommendations are made for the practice and for further research.

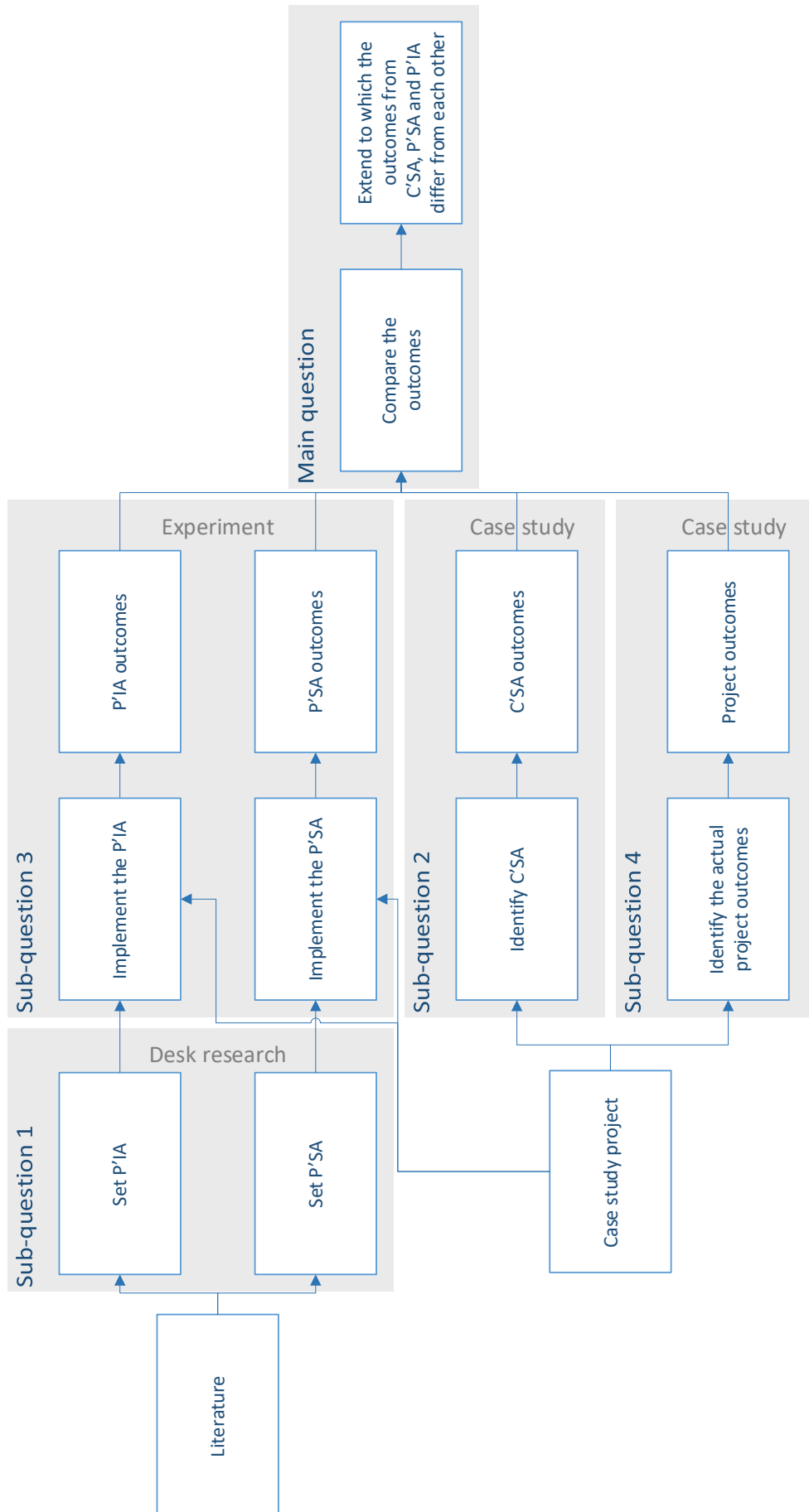


Figure 1: Research framework

2 THEORETICAL FRAMEWORK

In this chapter the theoretical framework within which the research will develop is established. This is essential since many of the terms surrounding the topic of risk analysis are ambiguously defined and thus have many interpretations, causing confusion, even among experts. Therefore, an effort is made to explain and unambiguously define the concepts and terms that will be used throughout the report, so that the intended meaning is emitted, and confusion is avoided. First, the terms uncertainty and risk are clarified and decomposed in individual elements. Then a layout of the very broad project management field is presented and used to position the quantitative risk analysis process. Finally, the P'SA and P'IA are explained, and their procedures are defined.

2.1 UNCERTAINTY & RISK

In literature and daily practice, the terms “risk management” and “risk analysis” are most often used instead of “uncertainty management” and “uncertainty analysis” (Chapman & Ward, 2003). Other times they are used interchangeably as if they have the same meaning. The terminology itself does not matter, as long as the context is universally understood. However, in the risk management community there is no commonly agreed terminology, a term has often multiple interpretations and therefore the context is often misunderstood. In the following paragraphs, some typical points of confusion will be explained, and the terminology used in this research will be clarified.

A definition of risk from the PMBOK® Guide follows (PMI, 2017):

“Risk is an uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives such as scope, schedule, cost, and quality.”

This definition implies that risk management refers to the management of only the risk events, which may or may not occur and have an impact on the project objectives. In practice however, risk is often used with a broader meaning where it encompasses all elements of uncertainty. As is shown later in paragraph 2.2, there are several classifications for the elements of uncertainty, and risk event is only one of them. In such a context, risk management has the broader meaning of managing all the elements of uncertainty, not only risk events.

Substituting the terms “risk management” and “risk analysis”, with the terms “uncertainty management” and “uncertainty analysis”, would apparently remove any confusion. Unfortunately, the term “uncertainty” is also ambiguously defined in practice. It is most often used to describe another specific element of uncertainty as shown later (Hulett et al., 2011).

The extend of confusion on the terminology in the risk management field now becomes apparent and the following quotes from Chapman and Ward (2003) summarize it nicely:

“It could be argued that this starting point means we are talking about ‘risk and uncertainty management’ or just ‘uncertainty management’ (including risk management), not ‘risk management’.”
“...but the term ‘project risk management’ is too well established to be replaced widely in the near term and is retained for this book.”

In this research the following will apply. The terms “risk” and “uncertainty” will have the same broad meaning of encompassing all the elements listed in Table 2. Therefore, “risk management” and “uncertainty management” are the same, “risk analysis” and “uncertainty analysis” are the same, and can be used interchangeably. The next paragraph describes what specific elements of uncertainty are included in this research and how they will be called.

2.2 UNCERTAINTY ELEMENTS

As already mentioned, there is a lot of confusion in the risk management field (Chapman & Ward, 2003; Hillson, 2012). This confusion stretches from the major concepts, like risk management itself, all the way to the smaller components that shape up the field. As a result, there is no set of uncertainty components to be accepted universally as the correct one. Nevertheless, it is important to identify and follow a set of components so that uncertainty can be decomposed into smaller more manageable pieces which can then be simulated in a quantitative risk analysis. Only then can the different uncertainties be represented appropriately in the models and only then realistic and useful outcomes can be obtained.

In literature several classifications for the elements or types of uncertainty exist. De Meyer, Loch, and Pich (2002) classify uncertainty into four types based on the difference in management styles that is effective for each type. They identify the types of variation, foreseen uncertainty, unforeseen uncertainty and chaos. Vrijling (2009) classifies uncertainty into three categories, namely uncertainty related to normal events, uncertainty related to special events and project uncertainty. Chapman and Ward (2003) classifies uncertainty into four types, namely risk events, inherent variability, ambiguity and systemic uncertainty. Hulett et al. (2011) distinguish the types of risk events (or just risks) and uncertainties. This constitutes the most widely used classification, but paradoxically the names of the specific elements are the same as the names of the broader notion.

Despite the plethora of names assigned to uncertainty classes from the abovementioned researchers, some of the classes represent similar types of risks. To make the connections clear, Table 1 matches the two uncertainty classes identified by Hulett et al. (2011) with the corresponding classes from the rest of the sources.

Table 1: Matching the different classes

Literature	Uncertainty classes	
Hulett et al. (2011)	Risks	Uncertainties
Chapman and Ward (2011)	Risk events	Inherent variability
De Meyer et al. (2002)	Variation	Foreseen uncertainty
Vrijling (2009)	Uncertainty related to normal events	Uncertainty related to special events

For this research the two uncertainty types classification from Hulett et al. (2011) is adopted, but the naming is taken from Chapman and Ward (2011), as it avoids creating confusion with the broad notions of the terms uncertainty and risk. Finally, an important contributor to uncertainty is correlation. Correlation is included only in the classification of Chapman and Ward (2011), under the systemic uncertainty type, but it is mentioned in almost every risk analysis document (R. P. Covert & Covarus, 2013; Duncan, John, Alfred, & Jeff, 2014; Hillson, 2012; Hulett et al., 2011; Sonmez et al., 2007; Vrijling, 2009). Because of its importance, correlation is included in this report alongside risk events and inherent variability. The three elements are listed in Table 2 and elaborated in the following paragraphs.

Table 2: Uncertainty elements

Uncertainty element	Probability	Impact
Risk events	<100%	Probability density function
Inherent variability	100%	Probability density function
Correlation	<100%	Correlation coefficient, model logic

2.2.1 INHERENT VARIABILITY

Inherent variability encompasses all the small factors that can influence an estimate. Each of these factors in isolation does not produce a considerable contribution to uncertainty. Therefore, it would be extremely impractical and inefficient to investigate each and every one of the factors independently, and will be of no value in the end (De Meyer et al., 2002). This is the reason why this element of uncertainty is not identified nor given attention in a qualitative risk analysis, where only impactful discrete risk events are assessed. The aggregate effect of these factors however, is significant and should not be ignored. Inherent variability describes the fluctuation caused by these numerous factors that create a steady but random distribution of output around the average of the data. In other words, it is the noise around an estimate. As the project progresses and more information becomes available, some of the factors contributing to inherent variability may be more clearly defined and find their way into discrete risk events.

Inherent variability is always present. Therefore, when simulated in a model is given a 100% probability of occurring. The impact of inherent variability looks like a fluctuation around a value. This is better simulated by a continuous probability distribution function. The following distribution functions, also depicted as graphs in Figure 2, are used to simulate inherent variability impact on cost and schedule elements in a MC analysis:

- Triangular or Trigen distribution
- Uniform distribution
- Normal distribution
- Beta distribution

A more elaborative description of probability distributions can be found in Appendix 1.

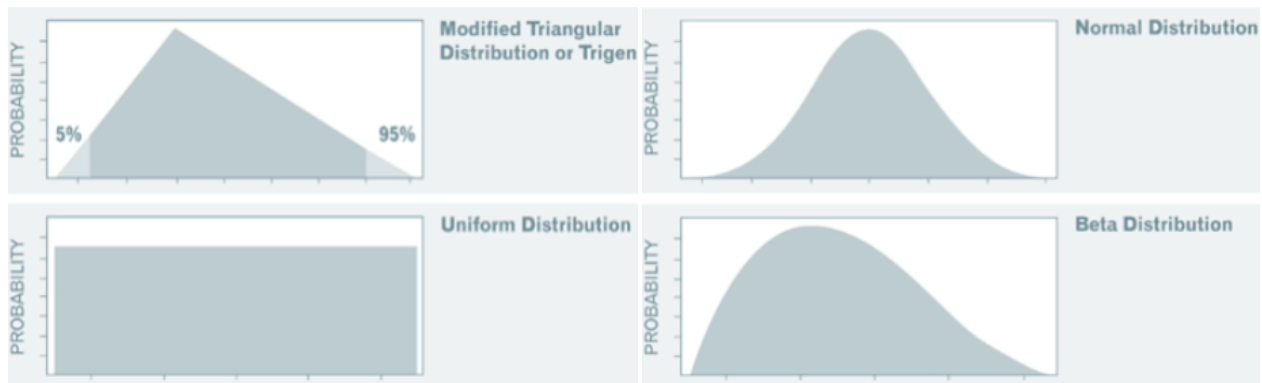


Figure 2: Typical continuous probability distributions used in Monte Carlo analyses (Hillson, 2012)

2.2.2 RISK EVENTS

Risk events are discrete, identifiable events that may or may not occur during the project. If they occur they will impact the project objectives, may that be the schedule, the cost, the safety or any other. Often in practice, risk events are related to events with negative impact and the term opportunities is used for events with a positive impact (Chapman & Ward, 2003). In this research, risk events encompass both positive (opportunities) and negative (threats) occurrences.

Qualitative risk analysis deals exclusively with the assessment of risk events. The risk register is nothing more than a list of all the identified risk events along with details regarding their main properties. A basic risk register should include at least details about risk events' pre-mitigated impact scorings, pre-mitigated probability scorings, mitigation measures, post-mitigated impact scorings and post-mitigated probability scorings.

In a quantitative analysis what matters is to correctly simulate the risk events' probabilities and impacts. Regarding the probability, two states can be identified. A risk will either occur or not. Therefore the probability of a risk event should be represented with a Bernoulli distribution (Figure 3) which is a discrete probability distribution that applies when there are only two possible outcomes (Purnus & Bodea, 2013). Contrary, the impact of a risk event is exposed to inherent variability. Therefore, it is most often simulated using a continuous probability distribution (Figure 2), in line with what is described above for inherent variability.



Figure 3: Bernoulli-discrete probability distribution (Hillson, 2012)

2.2.3 CORRELATION

Correlation may or may not exist, thus less than 100% probability, and its impact can be described by dependencies in a system, correlations between system components and the logic of the model in general.

The concept of correlation is an elusive one. Although it is omnipresent in modern quantitative risk analysis, it is often misunderstood. Correlations show the degree to which a change on one random variable is linked with a change on another random variable (Sander et al., 2016). The quantity of correlation is expressed through a correlation coefficient, which can take values from minus one to plus one. A minus one correlation coefficient indicates a perfect negative correlation while a plus one indicates a perfect positive correlation. A zero value indicates that the two variables are independent of each other (Jonkman, Steenbergen, Morales-Napoles, Vrouwenvelder, & Vrijling, 2015).

When there is a positive correlation between two variables, as the value of one variable increases the value of the other is more likely to increase as well. Conversely, when there is a negative correlation between two variables, as the value of the one variable increases, the value of the other is more likely to decrease (Caddell et al., 2012). In case the value of the correlation coefficient is zero, it means that the value of one variable increases or decreases irrespectively of how the other variable changes. Of course, this is not a problem for unrelated variables, but this is not the norm in a project.

The cost of several elements and the durations of activities are usually related through common denominators. These can be the same contractor or the same physical location or anything else. It is expected then that a change in one cost element or task duration will at least be partially reflected in another (Risk Integration Management Pty Ltd, 2018). For example, a poor performance from a contractor will be evident in most of the activities he undertakes. Or a rise in steel prices will cause a rise in both structural steel cost elements and reinforcement bars cost elements.

Correlation works on continuous distributions and thus can be applied on elements for which inherent variability is assigned. It is not applicable though for Bernoulli distributions. Therefore, potential dependence between risk events should be simulated in another way, like event trees analysis. This research however does not deal with this kind of relation and the risk events are considered independent of each other.

A more elaborative description of correlations can be found in Appendix 1.

2.3 PROJECT MANAGEMENT, RISK MANAGEMENT & RISK ANALYSIS

According to the PMBOK® Guide (PMI, 2017), project management is “the application of knowledge, skills, tools and techniques to project activities to meet the project requirements”. As expected, the definition of project management is itself very broad and encompasses many processes associated with various knowledge areas, in all the stages of a project. Risk management is listed as one of the ten knowledge areas within project management as depicted in Figure 4, and is composed out of several processes (PMI, 2017).

According to ISO 31000 (2009), risk management is defined as “coordinated activities to direct and control an organization with regard to risk”. Multiple objectives can be set for risk management and numerous risk management frameworks exist in literature with different steps and processes. However, in principle any risk management framework should include the following important steps (Hillson, 2012):

1. Define objectives
2. Identify relevant uncertainties
3. Prioritize uncertainties for further attention
4. Develop appropriate responses
5. Report results to key stakeholders
6. Implement agreed-upon actions
7. Monitor changes to keep up-to-date
8. Learn lessons for the future.

Most standards that cover the topic offer similar approaches that embody these steps. Figure 5 shows the steps for project risk management as presented in the following standards:

- ISO 31000:2009 - Risk Management - Principles and Guidelines from the International Organization for Standardization (ISO 31000, 2009)
- PMBOK® Guide - A guide to the Project Management Body of Knowledge 6th edition - Project Management Institute - Chapter 11-Project Risk Management (PMI, 2017)
- IPMA ICB v4.0 - Individual Competence Baseline for Project, Program & Portfolio Management version 4.0 - International Project Management Association (IPMA, 2015)

As demonstrated in Figure 5, the processes from the different standards have similar structures. In fact they are homogeneous enough so that the following common framework with five phases can be established (Purnus & Bodea, 2013):

- Initiation
- Identification
- Assessment
- Response
- Monitor and control

While these five steps/processes seem to be discrete elements that have a clearly defined order, in reality the interfaces are softer and the processes overlap and react with each other (PMI, 2017). Also, some of the steps should be performed several times in a project. Uncertainty is not a static concept, it evolves as the project unfolds, so should the risk management practice if it is to be efficient and effective.

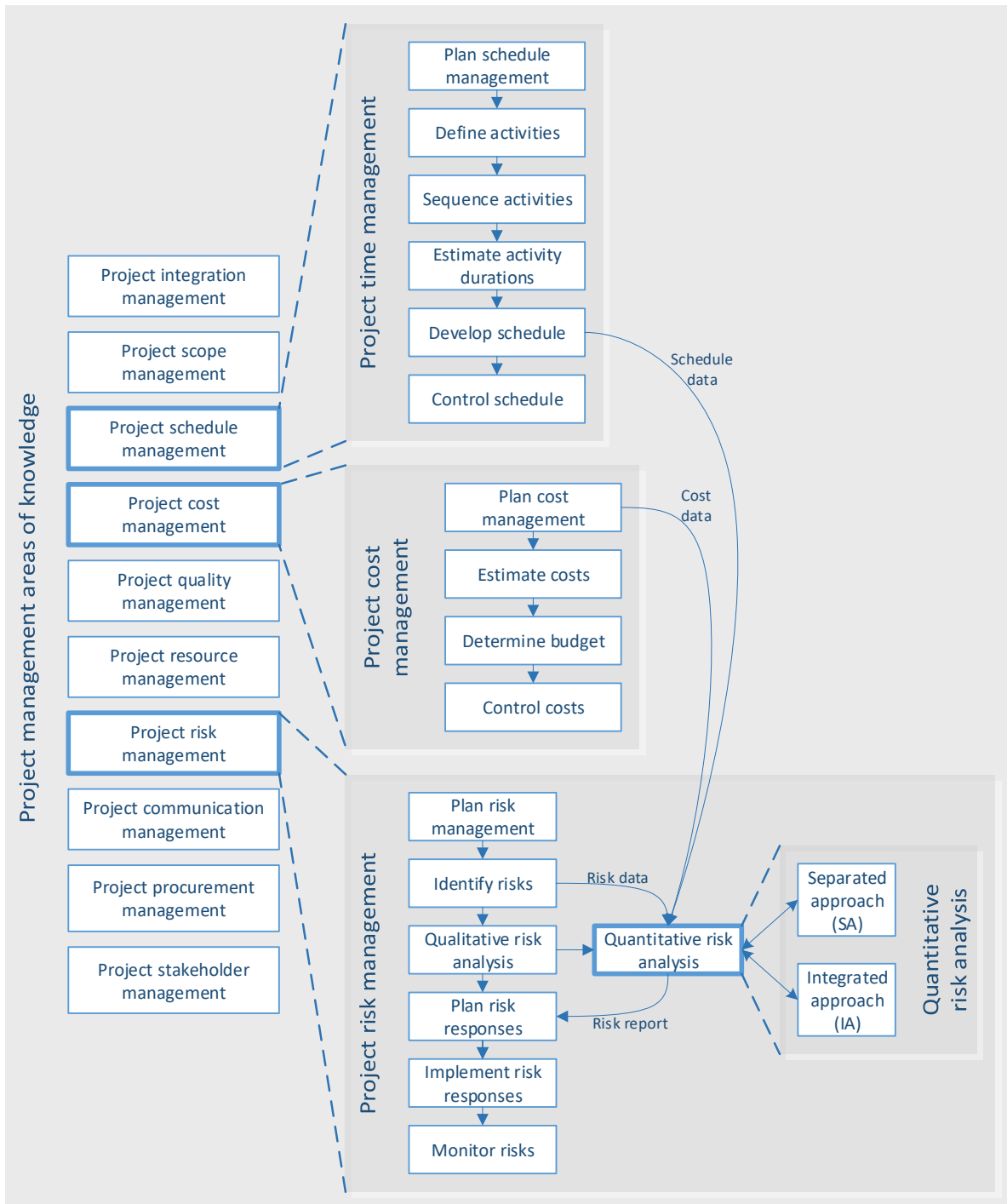


Figure 4: Positioning risk analyses, adapted from PMI (2017)

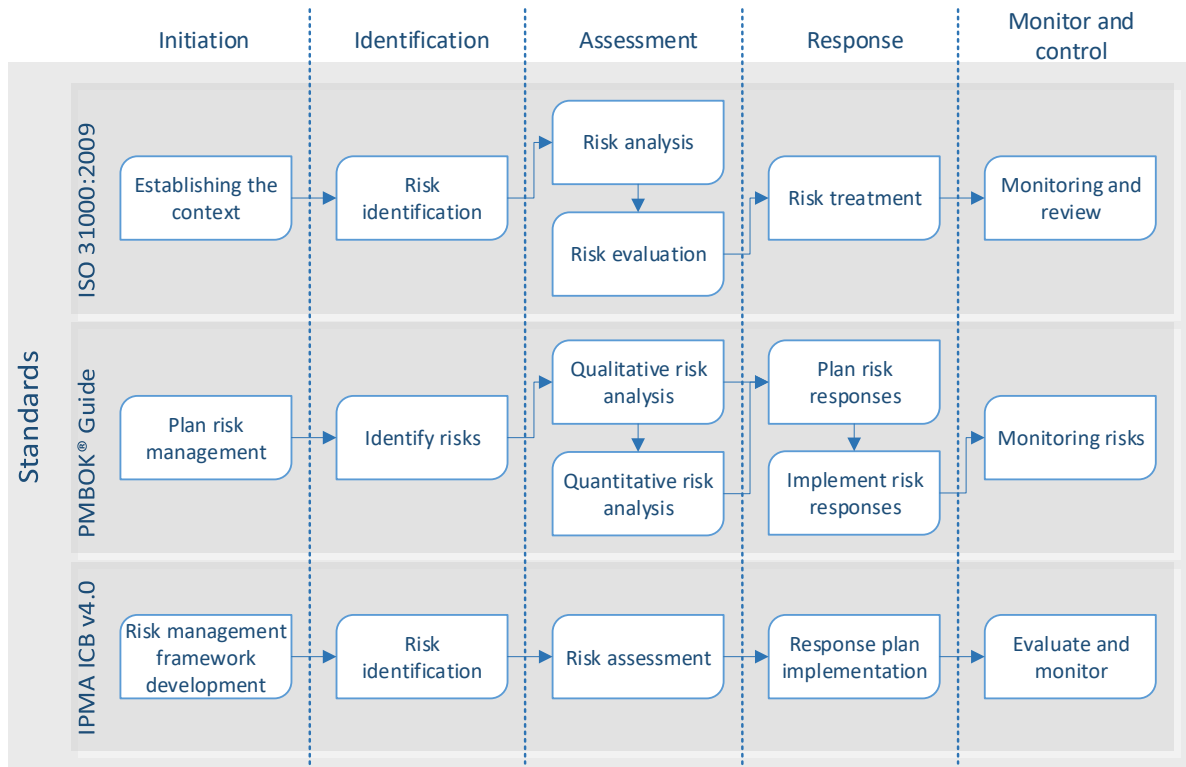


Figure 5: Project risk management processes from different standards

The assessment phase is widely viewed as the most critical to achieve effective risk management (Purnus & Bodea, 2013). Risk analysis is the main component of this phase. It is the process that leads to the development of an understanding of the risks (ISO 31000, 2009). In general, all risk analyses can be classified in two categories, the qualitative and the quantitative one. Because of their importance they are considered as core processes in the broader risk management area (Purnus & Bodea, 2013).

2.4 QUALITATIVE RISK ANALYSIS

Particularly, during a qualitative risk analysis, the risk events identified in the previous step (Identification) are prioritized by assessing their probability of occurrence and their impact on project objectives. Usually a qualitative scale is created, divided in intervals that form levels, which are then used to classify and describe the likelihood of a risk event and its severity of impact (Hillson, 2012; Nicholas & Steyn, 2017). By prioritizing the risk events, the organization can focus on the risk events that matter. Based on the prioritized risk register, and depending on the company's risk tolerance, a response plan can be laid down for the top-rated risk events.

The qualitative risk analysis is easier and simpler to execute within a short time frame compared to a quantitative one. It does not require specialized knowledge and is well established in the risk management practice. Usually the qualitative analysis provides the first opportunity to acquire valuable insights about the exposure of the project to risk events and it should always be performed (PMI, 2017).

Nevertheless, the qualitative risk analysis has several limitations. An overall measure of the effect of risk events on project objectives cannot be derived (Hillson, 2012). Uncertainty elements, other than risk events, cannot be incorporated. Because of its qualitative/descriptive nature, the results can be exposed to different interpretations. It does not provide a high-level detail of the effects of risks, which may be needed to assist decision making. Despite all the limitations, in most projects the qualitative

analysis is thought to be sufficient for understanding and dealing with the risks. In these projects, time and cost estimates are calculated in a deterministic manner.

2.4.1 DETERMINISTIC COST AND SCHEDULE ESTIMATING

Figure 6 shows the procedure followed for the deterministic cost calculation, which takes place within the cost management field (Figure 4). The cost elements, as identified in the cost breakdown structure together with their respective point estimates are used to develop the deterministic cost model. This model is usually in the form of a spreadsheet and the calculation of the deterministic cost is a simple summation of the individual cost components.

Until this point, the procedure is clearly deterministic without any appreciation of uncertainty. Estimators would rarely stop here and take this cost estimate as the final one. It would give an overly optimistic estimate for cost that will not represent reality. To avoid this situation and reckon for the undeniable existence of uncertainty, a common practice is to add a percentage of cost contingency as presented in Figure 6. As already mentioned, the percentage is decided based on past experiences from similar projects and from the outcomes of the qualitative risk analysis (Mak & Picken, 2000; Senesi et al., 2015; Sonmez et al., 2007). This method has the advantage of being easy and fast and can work well for simpler projects. It is however very abstract and provides no insights on the sources of uncertainty (Harishkumar & Pravin, 2016). In larger and more complex projects such insights are invaluable. Finally, the deterministic estimate along with the contingency estimate form the cost baseline. This is the reference against which the cost development in a project will be compared, for monitoring and controlling purposes.

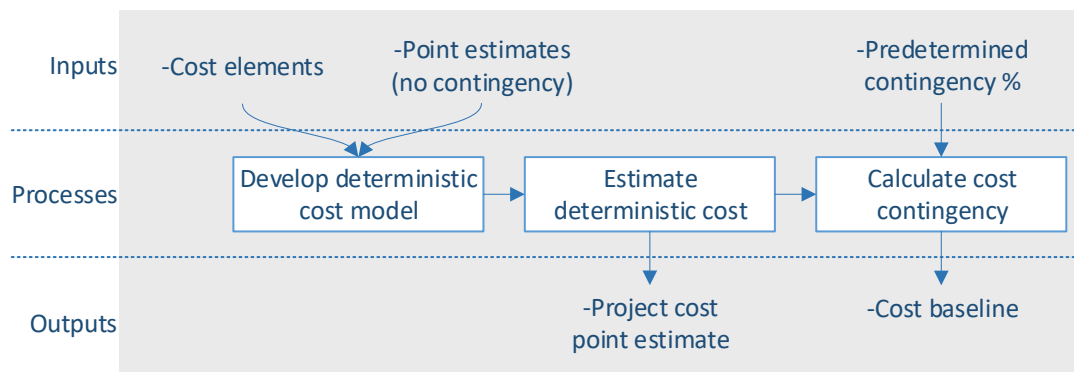


Figure 6: Deterministic cost estimation procedure

Figure 7 shows the procedure for the deterministic calculation of project duration which takes place in the time management knowledge area (Figure 4). The activities with their respective point estimates for duration along with the network logic, compose the deterministic schedule model. This model has normally the form of a Gantt chart. The calculation of the project duration, contrary to the project cost approach, is not merely a summation of the durations of the individual activities. Instead, the Critical Path Method (CPM) is used to determine the project duration and subsequently the project finish date.

Similar to the cost estimation procedure, up to this point there is no appreciation for uncertainty. Again, a predetermined schedule contingency percentage, based on hints from the qualitative risk analysis and past experiences, is added to the calculated deterministic duration to bring it closer to reality. The produced schedule baseline is then the reference against which the schedule progress is compared.

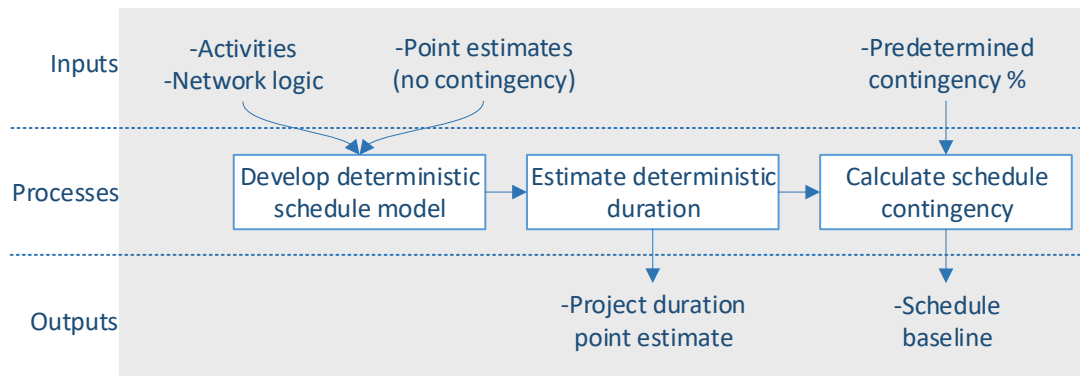


Figure 7: Deterministic time estimation procedure

2.5 QUANTITATIVE RISK ANALYSIS

While qualitative risk analysis should always be performed in risk management, quantitative risk analysis is often omitted (PMI, 2017). Whether it will be implemented or not depends on the project complexity and the adequacy of the qualitative outcomes. Bigger or innovative projects that are inherently riskier, require a deeper understanding of the underlying uncertainties, than what the qualitative analysis can provide. In such cases a quantitative risk analysis is performed as well. Nevertheless, as the importance of risk management becomes more evident, more attention from companies is given to tools and methods that quantify and incorporate uncertainty in cost and time analyses. Generally, it is recommended that both analyses are performed (Hillson, 2012).

In quantitative risk analysis, statistical analysis techniques are implemented to numerically analyze the combined effect of uncertainty on project objectives. MC analysis, decision trees, influence diagrams, fuzzy approaches are some of the techniques that are utilized to perform a quantitative risk analysis (Hillson, 2012). Even though, probabilistic approaches like MC method are not new in literature (Levitt, Ashley, Logcher, & Dziekan, 1979), only a few years ago commercial software packages were developed to support such analyses (Senesi et al., 2015).

The most common approach is to perform a quantitative risk analysis by means of a MC simulation. MC method works by generating random samples from given distributions to obtain a numerical result for a model. Through multiple iterations of this process, a distribution is obtained for the possible solutions for the model. Contrary to qualitative analyses, all uncertainty elements can, and should be incorporated in a MC analysis. Some elements of uncertainty, like risk events, can be transferred from the qualitative risk analysis, which should always precede a quantitative one (PMI, 2017). Inherent variability and correlations however, should be identified in the process of the quantitative analysis because they cannot be represented in a qualitative analysis. The inclusion of all the uncertainty types makes for a more comprehensive risk analysis.

Two fundamentally different approaches for probabilistic cost and schedule risk analysis can be followed. One option is to treat cost and schedule as completely independent entities, which implies carrying out two separate analyses. One for a model containing only cost related elements and one for a model containing only schedule related elements. The other option is to acknowledge the existence of a time-cost relation and to perform one integrated analysis using a single model in which both cost, and schedule related elements are included. These two approaches will be explained in the following paragraphs.

2.5.1 PROPOSED SEPARATED APPROACH (P'SA)

As mentioned, in most projects a deterministic approach is followed for schedule and cost estimating. For the few projects that a probabilistic technique is adopted, a SA is followed. That is, two separate and independent probabilistic risk analyses are performed, one for costs and one for schedule.

Figure 8 illustrates the procedure for the P'CRA. The uncertainty elements are identified during the "Identification" phase of the risk management process (Figure 5). Along with the cost elements, determined during cost management (Figure 4), they are used to assemble the probabilistic cost model. This is done by assigning quantified uncertainty elements to the components of the model wherever it is considered necessary. Like the deterministic cost estimation, the model still has a spreadsheet layout. A MC analysis is then performed on the model to calculate the project cost distribution and the cost risk events ranking. This distribution shows the probability that a certain cost value will be exceeded, or not, at project completion².

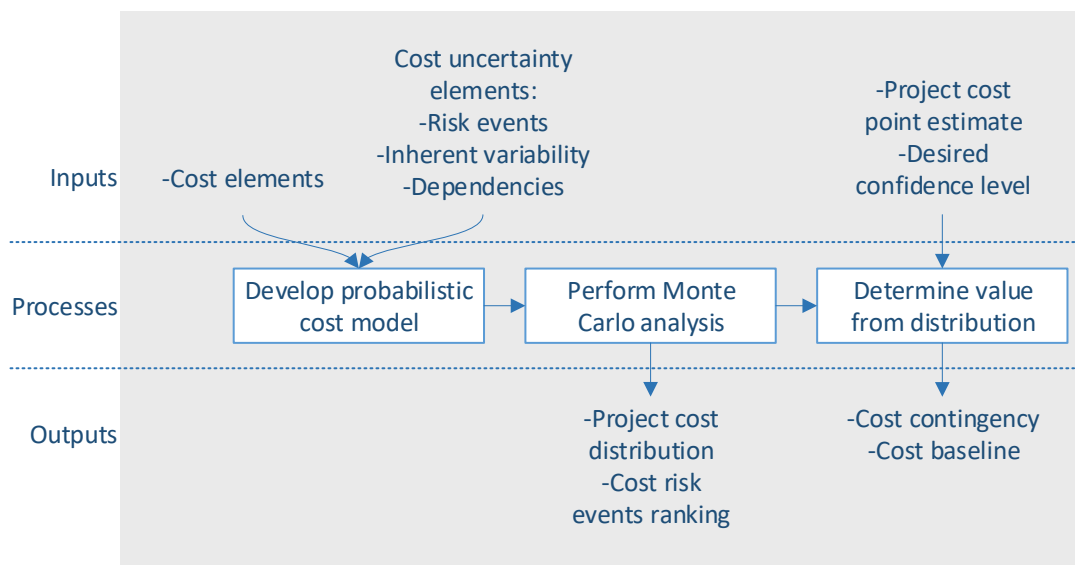


Figure 8: Proposed Cost Risk Analysis (P'CRA) procedure

Several opportunities arise from the distribution. For example, the deterministic estimates for cost can be assessed in terms of what is the probability of not surpassing them. Conversely, the values for cost can be derived for a desired confidence level. Usually in practice, a combination of the two workflows takes place to derive the cost contingency amount. First, the probability of not exceeding the deterministic estimates is identified. The values for the desired certainty level are identified as well. The difference between the deterministic estimates and the values corresponding to the desired confidence level is taken as the contingency amount. This contingency amount is then added on top of the deterministic estimates to form the baseline. This way the probability of staying within the estimates and not deviating significantly from the baseline will be up to an acceptable level.

The equivalent procedure for the P'SRA is shown in Figure 9. The activities, the network logic and the schedule uncertainty elements are collected to build the probabilistic schedule model. The model maintains the same Gantt chart form factor it has in the deterministic procedure. Through a MC analysis, the project duration distribution and the schedule risk events ranking are generated. Then, by

² The probability of not exceeding a specific cost or schedule value in intermediate stages of the project is also possible given that the model is appropriately adapted.

following a procedure analogous to the one in P’CRA, the schedule contingency is produced and added to the deterministic duration to form the schedule baseline.

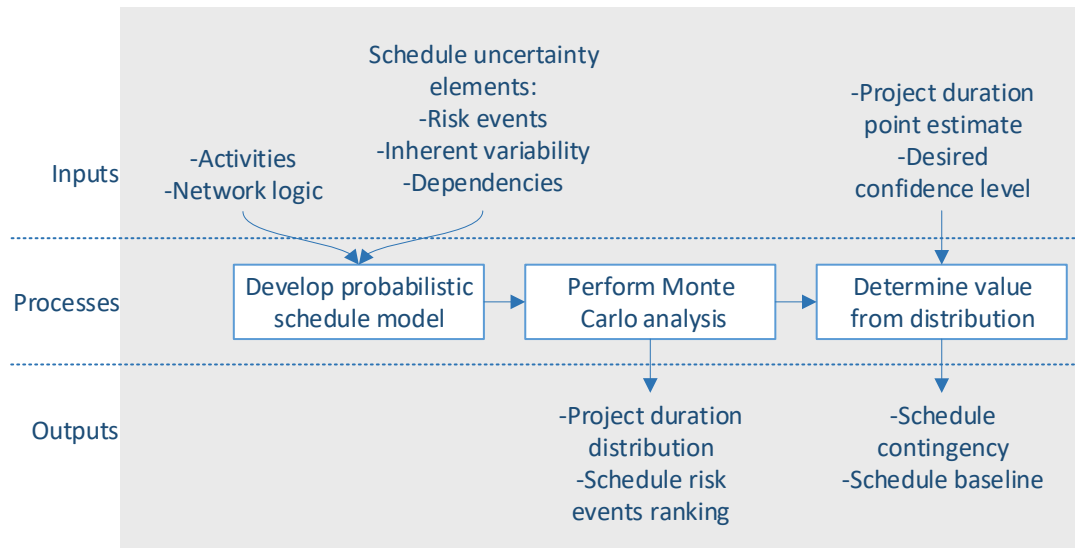


Figure 9: Proposed Schedule Risk Analysis (P’SRA) procedure

The P’SA as described, develops the cost and schedule baselines separately. Since time and cost elements are known to interact with each other, this approach disregards their relation. As Isidore and Back (2002) write in their work, *“This, therefore, makes it difficult to determine how the estimate and schedule for a specific project are related”*. So, the estimates produced by this approach do not reflect reality in that respect. Specifically, a SA fails to produce the cost variability caused by schedule uncertainties (Hulett et al., 2011). As a result, the cost contingency that is calculated for a specific confidence level is very likely incorrect as it is based on the wrong assumption that project cost is independent of project duration.

2.5.2 PROPOSED INTEGRATED APPROACH (P’IA)

The IA comes as an answer to the mentioned shortcomings. The immediate advantage of the IA is that, through a single ICSRA, the impact of schedule uncertainty on costs is taken into consideration. Therefore, the cost contingency produced by the IA is in principle more accurate (Hulett et al., 2011).

The procedure for the P’ICSRA is illustrated in Figure 10. In line with the cost related procedures described so far, the cost elements identified in cost management are required for the integrated analysis. However, before utilizing the cost elements further, it is necessary to classify them in time-dependent (TD) or time-independent (TI) cost elements. TD, or labor type, is called a resource that has a duration variable in its cost function. In other words, if a resource’s cost value is affected by time, viz. it costs more if “it takes more time” and costs less if “it takes less time”, then it is TD. Conversely, a resource is called TI or material type, if there is no duration variable in its cost function. In other words, duration fluctuations will not change its cost value. This distinction is vital to correctly simulate the behavior of cost elements in the integrated model.

Like the previously described schedule related procedures, activities and network logic are collected from time management teams to build the schedule model. The next step in the P’IA is to assign all the cost elements of the project appropriately on activities in the schedule model. This is called resource-loading or cost-loading. The purpose of that is to allocate the whole cost of the project on the schedule activities, so that changes in durations will be reflected on TD cost elements.

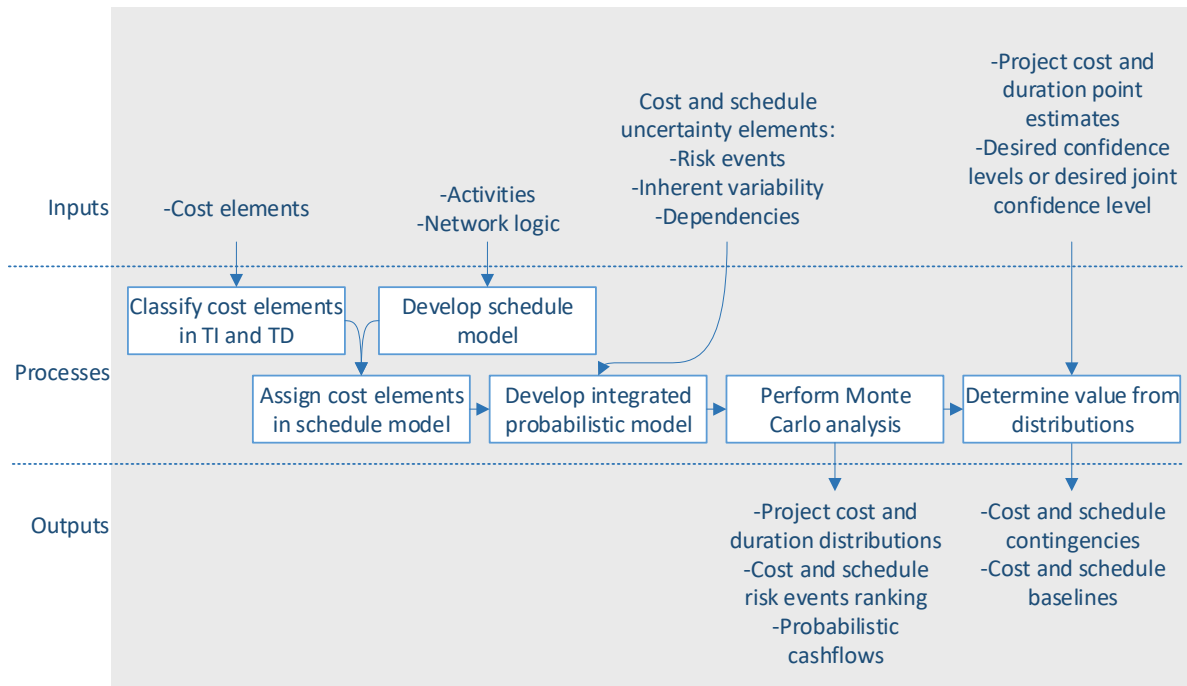


Figure 10: Proposed Integrated Cost and Schedule Risk Analysis (P'ICSRA) procedure

After the cost elements are mapped on the schedule, all uncertainty elements, both cost and schedule related, are assigned appropriately to create the integrated probabilistic model. With the model ready, a MC analysis is then performed. Distributions and risk events rankings for cost and schedule are generated. Like the previous probabilistic analyses, the deterministic cost and duration estimates and the desired confidence levels for duration and cost are reflected on the respective distributions to pinpoint the required contingency. In theory, this approach will produce a more accurate project cost distribution and consequently the cost contingency will be more realistic. Similarly, a more correct cost risk events ranking is expected to be produced. Contrary, schedule estimates and schedule risk events rankings do not change.

Furthermore, with the P'ICSRA additional capabilities become available. The cost and schedule contingencies can be selected based on the principle of a joint confidence level. This concept describes the joint probability that both cost and duration will not exceed a specific value. To make it clear, a requirement of 85% probability of not exceeding a certain cost value and a requirement of 85% probability of not exceeding a certain duration value does not translate to a requirement of 85% probability of not exceeding none. Neither it results to the product of the two probabilities because the cost and time variables are not independent (R. P. Covert & Covarus, 2013). Another exclusive outcome of the P'ICSRA is probabilistic cashflow. Probabilistic cash flow forecasts at any point in the project the value of the expected cost for a desired confidence level. If for example an 85% confidence level is selected, probabilistic cash flow will plot the cash flow curve that represents the expected cost with an 85% certainty throughout the project, from start to finish.

On the other hand, an IA comes with extra requirements and possible workload. Whereas in a SA there is no need for the cost and schedule teams to align their work methods, in an IA this is essential. The effort needed to undertake this alignment should not be underestimated. It is already a very complicated and resource intensive job to properly estimate the cost and duration of activities and perform the probabilistic analyses. This can be done on different levels of detail, in different phases of a project and on different activities. In a SA, the estimating and planning teams will choose the most

convenient way for them so that they can be as productive as possible. In an IA, however, all these parameters should converge (Hulett, 2004). In theory this will affect negatively one or both teams and make the process more conflicting and time consuming.

The potential benefits of the IA are slowly appreciated, and more research is conducted on the topic. Therefore, in recent years great strides/advancements have been made to make the approach more consumer friendly and bring it to the masses. Several software packages exist now that offer the capability of conducting an ICSRA. Big projects' clients, may that be private or public, are also aware of the trend and increasingly demand the submission of an ICSRA from the prospective contractors. Already, big players in the industry are considering following the IA for their risk analysis procedures.

2.6 IMPLEMENTATION OF THE APPROACHES ON A SAMPLE PROJECT

A small fictitious sample project will be used to illustrate the procedures and steps needed to implement the P'SA and P'IA. This simple execution of the approaches will assist in a better understanding of the procedures.

SAMPLE PROJECT

The sample project consists of 13 activities, 3 of which are summaries (Table 3). For each activity a duration is assigned. This duration represents the most likely value. For the summary activities, duration is dictated by their underlying activities and needs not to be assigned. The activities are then linked with each other by using the four main types of relationships. In the sample project only "Start to Finish" type relationships were used. For the first activity of the project, a start date is assigned as there is no predecessor activity to be attached. This date represents the start date of the whole project. With all the above-mentioned data in place, the network logic of the project is established. The resulting Cantt chart is shown in Figure 11.

Table 3: Activities and their respective most likely durations (sample project)

Activity	Duration
Sample Project	320 days
Activity 1	40 days
Activity 2	50 days
Path A	140 days
Activity 3A	40 days
Activity 4A	45 days
Activity 5A	55 days
Path B	115 days
Activity 3B	40 days
Activity 4B	35 days
Activity 5B	40 days
Activity 6	30 days
Activity 7	60 days

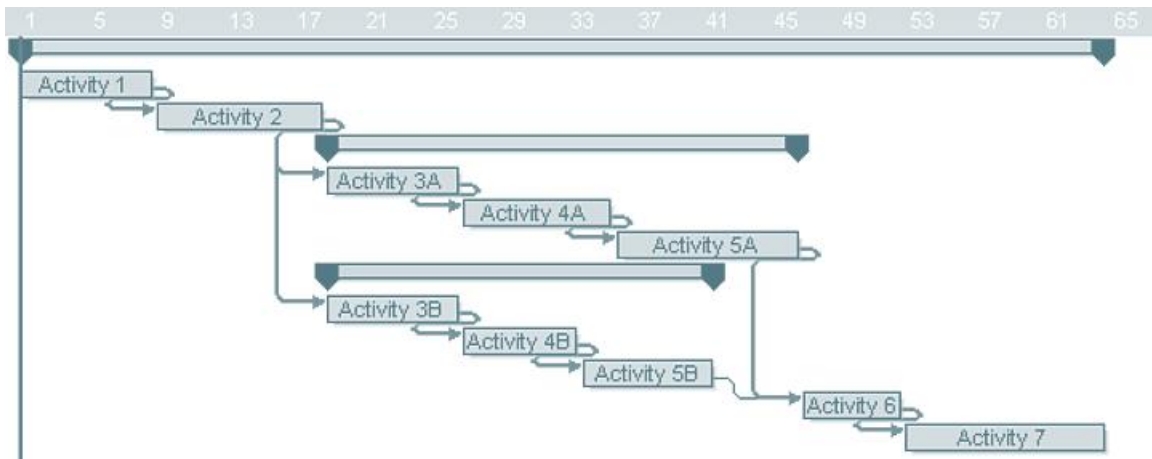


Figure 11: Gantt chart (sample project)

For the cost part of the project resources are required. Resources can be as detailed as specific employees or materials. Conversely, they can be summarized and grouped together at the level of a discipline or a project phase. In any case, when the resources are allocated to their respective work packages, a cost will be calculated for that work package.

For the sample project, the 7 resources shown in Table 4 were created. For each resource a “Cost rate” (cost per unit of resource per unit of time), and the “Required units” are defined. Similar with the “Duration” values discussed above, these values represent the most likely or best guesses. Finally, the total cost of every resource is the product of “Cost rate” multiplied by the “Required resources”.

Table 4: Resources and their respective most likely costs (sample project)

Name	Cost rate	Required units	Cost
Resource 1	100€	1500	150000€
Resource 2	100€	200	20000€
Resource 3	300€	500	150000€
Resource 4	200€	1400	280000€
Resource 5	300€	1000	300000€
Resource 6	200€	250	50000€
Resource 7	100€	250	25000€
Total project cost			975000€

DETERMINISTIC

In a deterministic approach, the estimates on cost and time are derived directly from calculations with the most likely values. The estimate for the finish date is calculated directly from the network logic using the CPM. According to the CPM, the critical path is determined by the longest (in duration) path of planned activities leading to the end of the project (Nicholas & Steyn, 2017). For the sample project only two alternative paths exist, A and B (Figure 11), out of which, path A is the critical one. The deterministic finish date of the sample project is 19/07/2019, while the deterministic duration is 320 days. In a real project thousands of alternative paths may exist, but the calculation of the critical path, and consequently of the finish date and the duration, follow the same principle.

For cost estimation, the calculation is simpler. The total cost estimate is just the summation of all the individual resources’ total costs. In the sample project, the deterministic total cost is calculated to 975000€ (Table 4).

The contingency for cost and time may be taken as a percentage of the point estimate. For the sample project, if a 10% is considered an adequate and representative value for the expected uncertainties, the resulting cost contingency is 97500€ and the resulting schedule contingency is 32 days.

PROPOSED SEPARATED APPROACH (P'SA)

The SA has several variants, but the main point of interest is that CRA and SRA are performed independently. The P'SA introduced in paragraph 2.5.1 is described in more detail.

As with the deterministic approach, the schedule with the network logic and the resources of the project are required. The next step is to incorporate the uncertainties. This is done for the activity durations and for the resources independently. Uncertainty is driven by risk events, inherent variability and correlations. First, the risk register is created. It is normally created regardless of whether a quantitative risk analysis will be performed, but then it is of a qualitative nature, as explained in paragraph 2.4. For the incorporation of risk events into the analysis however, quantification of the risk register should take place. This means that instead of scorings, distributions are attached to probability of occurrence and impact for every risk event. Risk events can then be assigned to their corresponding elements.

In the separated approach, two risk registers will be created. One with the risk events that have an impact on the schedule and one with the risk events that have an impact on the costs. Also, for the sample project no distinction of pre- and post- mitigated impacts is made, as it does not contribute to the research.

The quantified risk register for costs is shown in Table 5 and for schedule in Table 6. In accordance with paragraph 2.2.2, the impacts are represented as distributions because they are subjected to inherent variability. The triangle distribution was used to develop the schedule and cost impacts of the risk events. Of course, different distributions could have been selected and would probably produce different results. This is a debatable topic and numerous recommendations exist (Reynolds, 2012). For the sample project, the same probability density functions originally used by the company on the case study project are selected for consistency purposes.

Table 5: Cost risk events (sample project)

Risk name	Probability	Cost impact (€)			
		Distribution	Optimistic	Most likely	Pessimistic
Risk event 1	50%	Triangle	25000	50000	75000
Risk event 2	35%	Triangle	8000	16000	24000
Risk event 3	40%	Triangle	20000	25000	30000

Table 6: Schedule risk events (sample project)

Risk name	Impacted activity	Probability	Schedule impact (days)			
			Distribution	Optimistic	Most likely	Pessimistic
Risk event 1	Activity 3A	50%	Triangle	15	20	30
Risk event 2	Activity 4B	35%	Triangle	10	20	35

Next step in applying the uncertainties, is to assign inherent variability to the activity durations and the resources. Inherent variability describes the noise in an estimate and is usually described by three values, optimistic, most likely and pessimistic. From these three values a distribution is created. It is important that any consideration of risk event or opportunity is disregarded when developing the inherent variability (Hulett et al., 2011). For example, providing an overly pessimistic estimate on the

basis that something might happen that fundamentally alters the nature of the task to be performed, is not appropriate. In such a situation the uncertainty should be simulated by using a risk event.

For the resources, there are two input variables that are subjected to inherent variability, “Cost rate” and “Required units”. For each variable, an inherent variability distribution is given. A simpler alternative is to assign inherent variability directly to the “Total cost” of every resource, which is the product of the two inputs variables. Table 7 shows the inherent variabilities for the resources.

Table 7: Inherent variability on resources (sample project)

Name	Distribution	Cost rate (€)			Required units		
		Optimistic	Most likely	Pessimistic	Optimistic	Most likely	Pessimistic
Resource 1	Triangle	90	100€	105	1350	1500	1725
Resource 2	Triangle	90	100€	105	180	200	230
Resource 3	Triangle	270	300€	315	450	500	575
Resource 4	Triangle	180	200€	210	1260	1400	1610
Resource 5	Triangle	270	300€	315	900	1000	1150
Resource 6	Triangle	180	200€	210	225	250	288
Resource 7	Triangle	90	100€	105	225	250	288

The inherent variabilities assigned to the activities’ durations are shown in Table 8. Inherent variability is not assigned on summary activities. The duration for them is generated in every MC based on the durations and relationships of the underlying activities.

Table 8: Inherent variability on activity durations (sample project)

Name	Distribution	Optimistic	Most likely	Pessimistic
Sample Project	-	-	-	-
Activity 1	Triangle	36	40	48
Activity 2	Triangle	45	50	60
Path A	-	-	-	-
Activity 3A	Triangle	36	40	48
Activity 4A	Triangle	41	45	54
Activity 5A	Triangle	50	55	66
Path B	-	-	-	-
Activity 3B	Triangle	36	40	48
Activity 4B	Triangle	32	35	42
Activity 5B	Triangle	36	40	48
Activity 6	Triangle	27	30	36
Activity 7	Triangle	54	60	72

Final step in assigning the uncertainties is to define correlations that may exist between activity durations. Correlations describe the extent to which activity durations are related through a common denominator. For example, a longer duration in completing one activity may reflect on other activities because they are undertaken by the same contractor. In case correlations are omitted, the end distribution of the project duration will be more tightly grouped around the mean value and therefore the variance will be lower. Consequently, the values at selected confidence levels might differ dramatically from those coming out of a properly performed analysis. Therefore, assigning correlations is a very important task. For the sample project, all the resources distributions are correlated using a 0.4 correlation coefficient and all the duration distributions are correlated with 0.5 correlation coefficient (Appendix 1).

At this point all the uncertainties are identified and modeled. For the schedule part, risk events, inherent variability and correlations are all assigned to the activities of the project. For the cost part however, there is a structural difference. While inherent variability and correlations are assigned to the resources, risk events are not. In fact, risk event’s impacts are not assigned to a specific entity within the project. Normally they would be assigned to the affected activity. However, because the cost and schedule risk analyses are performed separately, this cannot be done.

Figure 12 shows the distribution from the P’CRA. From this distribution it is possible to observe for different confidence levels what is the expected overall cost. Reversely, for every overall cost value that materialized in the simulation, it is possible to observe what is the probability that it will not be exceeded by the actual overall cost. There is a 40% probability that the overall cost of the sample project will not exceed the determinist estimation of 975,000€. If a confidence level of 85% is desired, then a cost of 1,185,682€ should be considered. This entails a cost contingency of 210,682€.

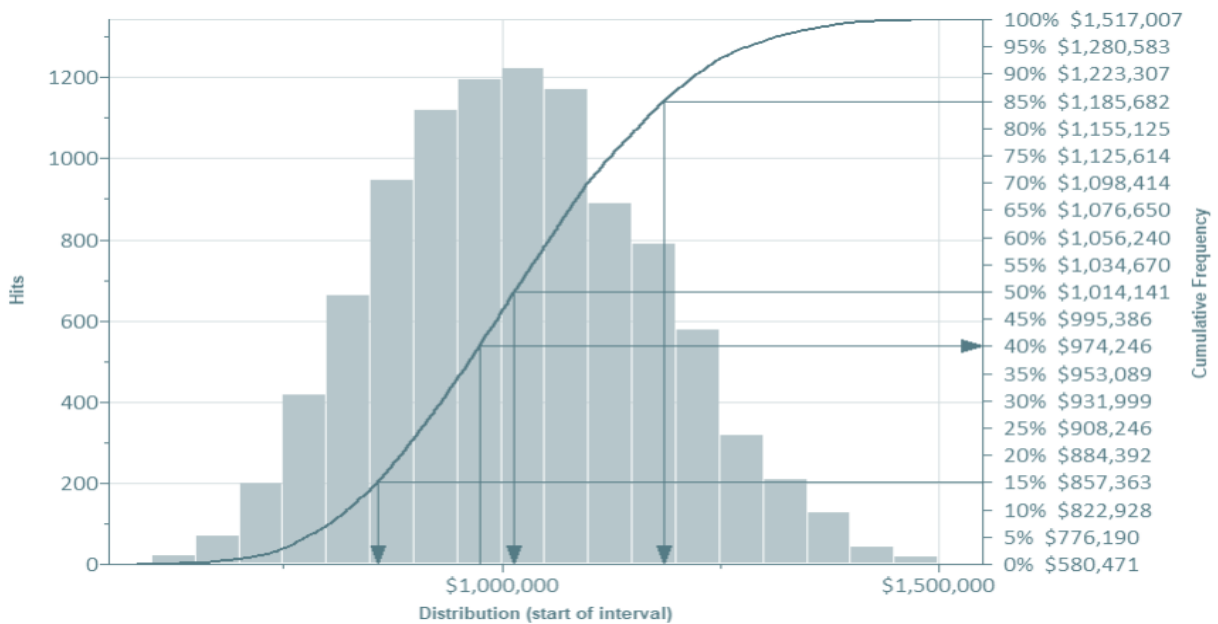


Figure 12: Overall cost cumulative and density distribution (P’CRA, sample project)

Figure 13 shows the risk events ranking according to their impact on the total costs of the project. The ranking is based on the correlation found between the occurrence of a risk event and the resulting total cost value during the MC analysis.



Figure 13: Cost risk events ranking (P’CRA, sample project)

Figure 14 shows the resulting distribution from the P’SRA.

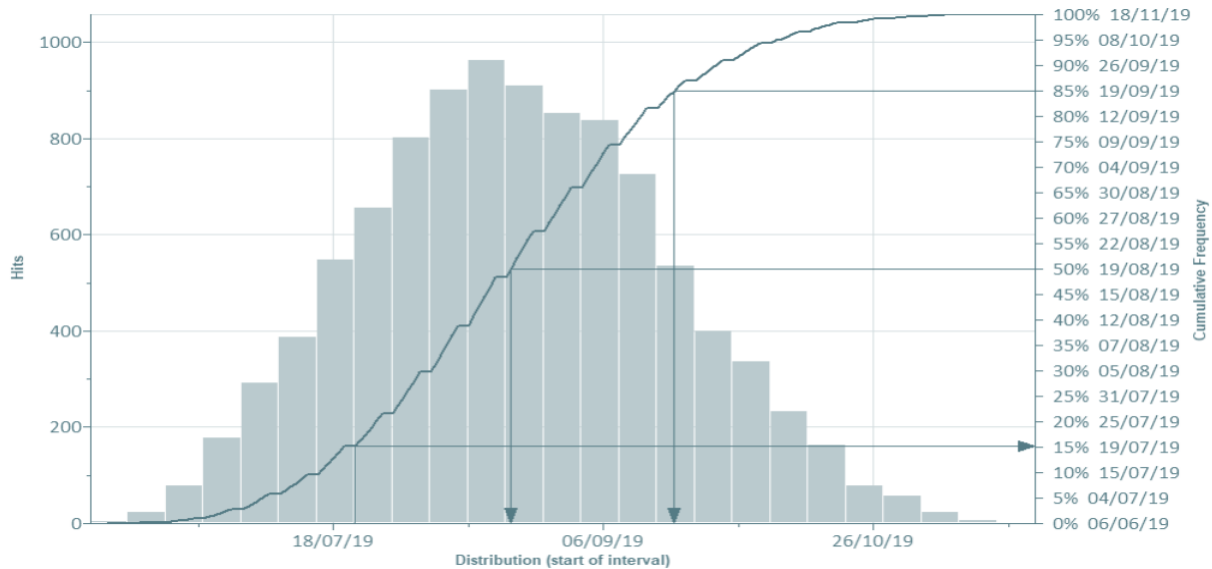


Figure 14: Finish date cumulative and density distribution (P'SRA, sample project)

The finish date point estimate is 19/07/2019. Based on the results of the simulation, there is a 15% chance that the project will finish by this date. If the managers want to have an 85% confidence level that the project will finish on time, then the finish date should be moved to the 19/09/2019. This necessitates a schedule contingency of 62 days.

PROPOSED INTEGRATED APPROACH (P'IA)

The procedure for the P'IA, as presented in paragraph 2.5.2, will now be described in more detail. As with the previous approaches, the schedule with the network logic, and the resources of the project are required. In the P'IA however these two elements must integrate. Every activity requires certain resources to be completed. So, the only thing to be done is to allocate the resources to the corresponding activities. The result of the integration is a resource loaded schedule. The allocation for the sample project is shown in Table 9.

Table 9: Resource allocation and types (sample project)

Activity name	Resource allocation	Resource type
Sample Project	Resource 1	TD
Activity 1	Resource 2	TD
Activity 2	Resource 3	TI
Path A	Resource 4	TI
Activity 3A	-	-
Activity 4A	-	-
Activity 5A	-	-
Path B	Resource 5	TD
Activity 3B	-	-
Activity 4B	-	-
Activity 5B	-	-
Activity 6	Resource 6	TD
Activity 7	Resource 7	TI

In principle, most activities require resources. Some of the activities in the sample project though, are not assigned any resources. Instead the resources for those activities are assigned to their summary tasks. This is a common practice and the resources are then called summary resources. This is how the

procedure was performed in the case study as well. When necessary more than one resources can be assigned on one activity. Additionally, a distinction should be made between TD and TI resources. As the name suggests, TD resources are those that cost more if they work more. Such resources include labor, management, rented equipment etc. TI resources are those whose cost is not affected by the duration of activities. Materials are the main example of such resource type (Hulett et al., 2011). The type of each resource in the sample project is shown in Table 9.

Next step is to assign the uncertainties on the integrated resource loaded schedule. First the risk register is created. In the P'IA, one risk register, with impacts on both schedule and costs, is created (Table 10). The difference from the P'SA is that, cost impacts are now assigned on specific activities, just like schedule impacts.

Table 10: Integrated risk register (sample project)

Risk name	Impacted Activity	Probability	Schedule impact (days)			Cost impact (€)				
			Distribution	Min	Most likely	Max	Distribution	Min	Most likely	Max
Risk event 1	Activity 3A	50%	Triangle	15	20	30	Triangle	25,000	50,000	75,000
Risk event 2	Activity 4B	35%	Triangle	10	20	35	Triangle	8,000	16,000	24,000
Risk event 3	Activity 7	40%	-	-	-	-	Triangle	20,000	25,000	30,000

Next step is to assign inherent variabilities and correlations where needed. For these steps the procedure is the same as the P'SA. At this point all the uncertainties are modelled. Contrary to the P'SA, all uncertainties are now incorporated in the integrated resource loaded schedule. It is possible to perform the P'ICSRA and get results for both, schedule and costs.

The overall cost distribution is shown in Figure 15.

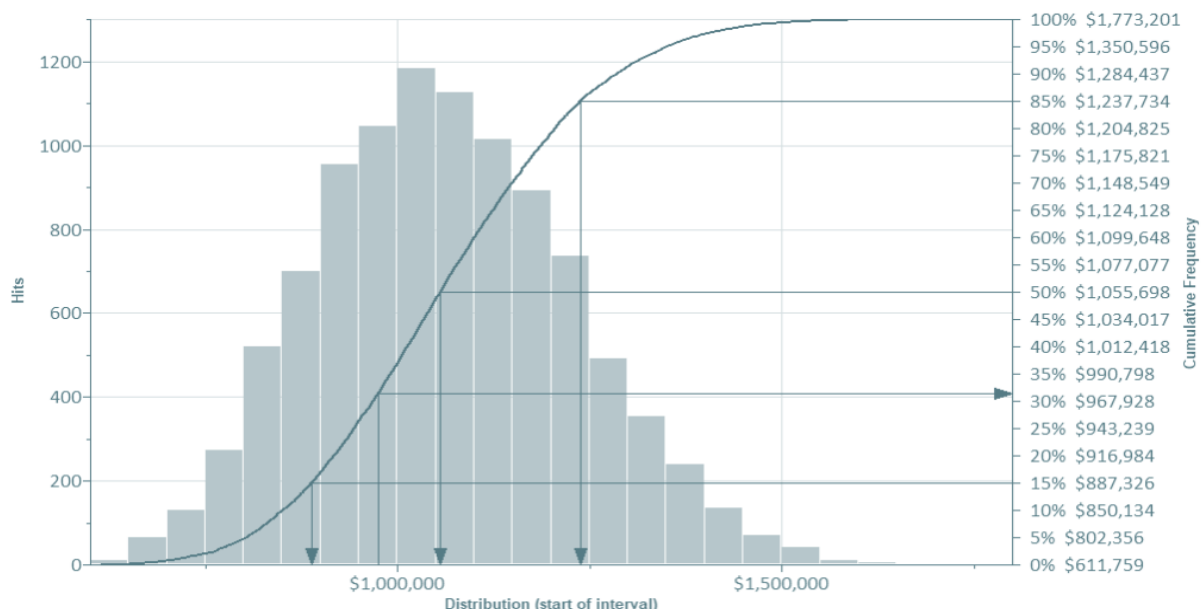


Figure 15: Overall cost cumulative and density distribution (P'ICSRA, sample project)

The probability of not exceeding the deterministic cost is now 31% compared to 40% in the P'SA. At the 85% confidence level, the corresponding cost figure is now 1,237,734€, compared to 1,185,682€ in the P'SA. The required contingency is calculated to 262,734€, compared to 210,682€. This is a substantial

difference and shows the scale of impact that the schedule uncertainty has on the overall cost distribution.

Figure 16 shows the risk events ranking generated from the P'ICSRA. The risk event ranking is different than the corresponding ranking from the P'CRA. Risk 2 is now ranked as the most impactful on the overall cost, whereas in the P'CRA it was risk event 1. The difference lies on the contribution of the schedule impacts on the cost variability which is considered only in the P'IA. The accumulated effect from cost and schedule impacts from risk event 2 is bigger than the accumulated effect of cost and schedule impacts from risk event 1. In the P'CRA only, the cost impact was considered for the ranking of the risk events and risk event 1 ended up on top on that respect.



Figure 16: Cost risk events ranking (P'ICSRA, sample project)

The schedule outcome is shown in Figure 17. The finish date distribution is the same as with the P'SRA. This was expected as all the schedule uncertainties were already incorporated into the simulation for the P'SRA.

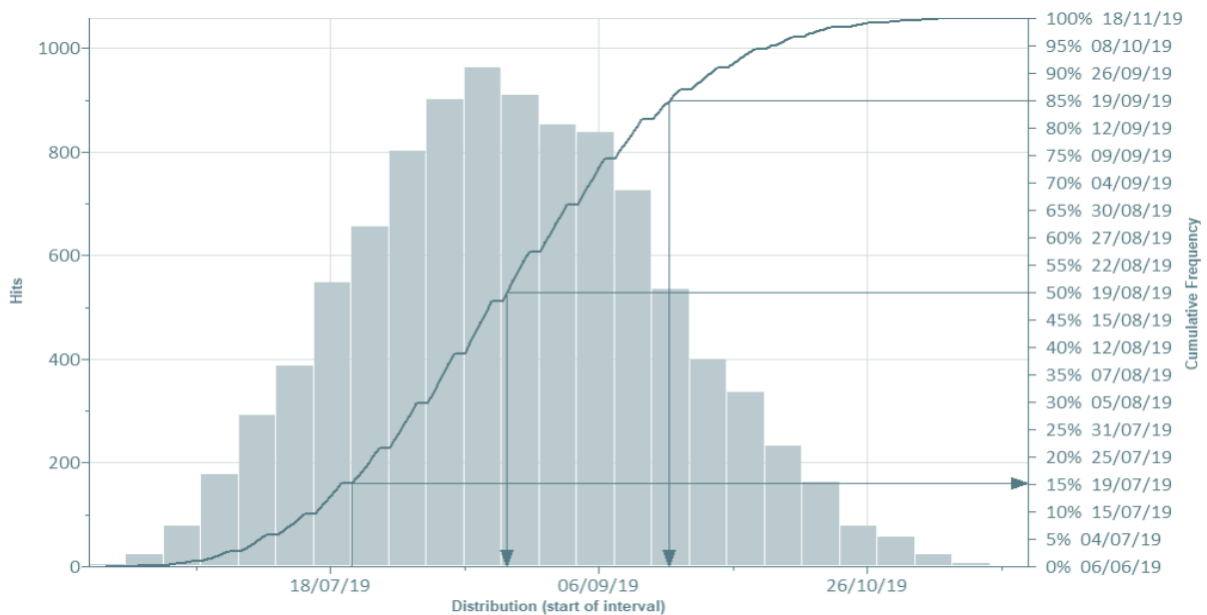


Figure 17: Finish date cumulative and density distribution (P'ICSRA, sample project)

Because of the integration of time and cost, some new graphs can be created that give better insights of the project. One such an example is the scatter plot shown in Figure 18. The scatter plot shows the relationship between two outputs of an analysis, cost and time in this case. Each point on the scatter plot represents two values for one iteration of the uncertainty analysis. The total number of points is equal to the number of iterations performed, 5000 in this case.

The 'cloud' that is formed by the points gives a visual representation of correlation as explained in more detail in Appendix 1. For the sample project, time and cost ended up 23.2% correlated (Figure 18). This means that when the duration is longer, it is more likely that the costs will also be higher.

The joint confidence level of time and cost is also an exclusive benefit of the P'IA and produced by the P'ICSRA. The joint confidence level says what is the probability that a project's cost will be equal to or less than a specific value and that the schedule will be equal to or less than a specific value. This can also be visualized through the scatter plot. For example, when the marginal confidence levels for time and cost are set to 85%, the joint confidence level is 74%.

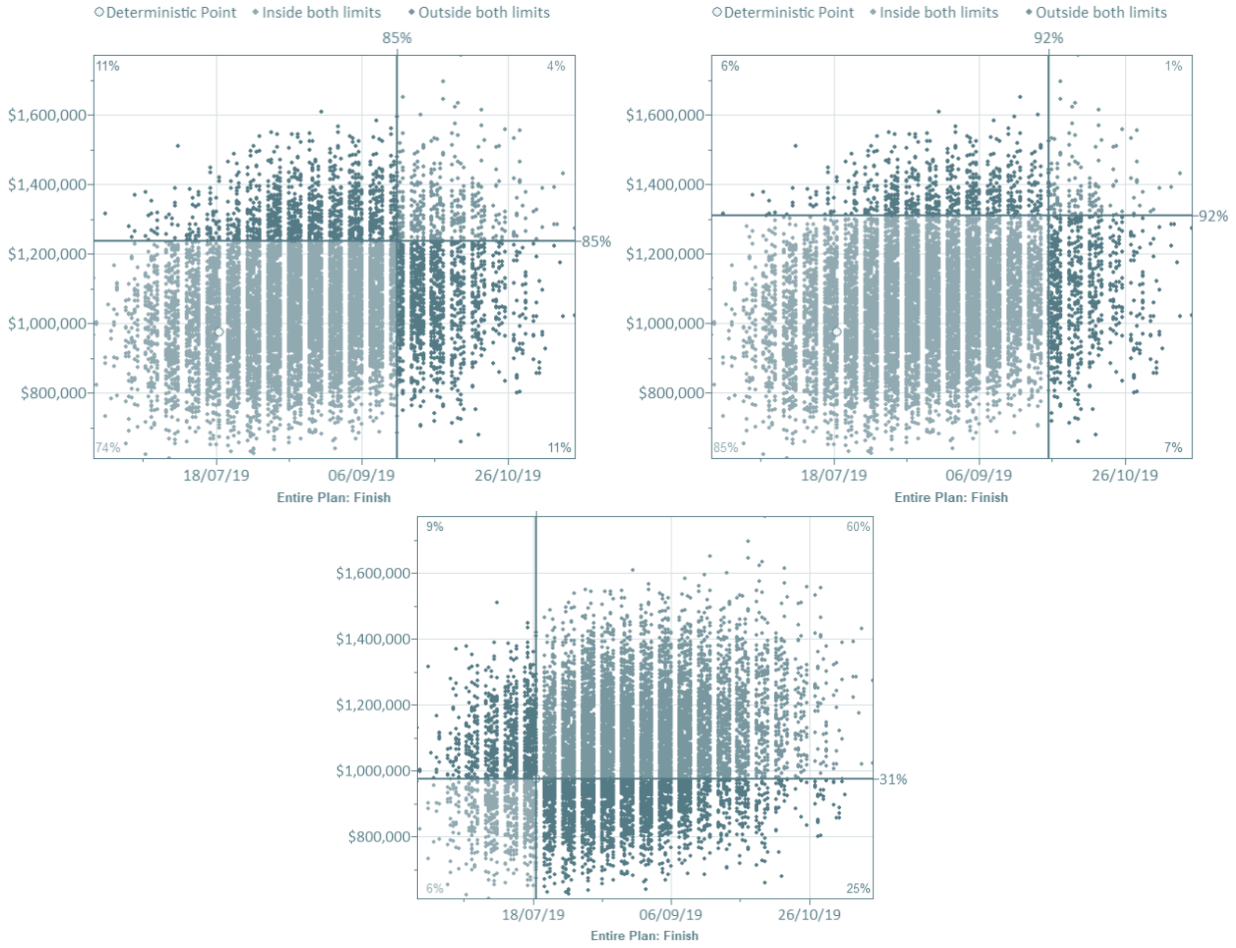


Figure 18: Scatter plot (P'ICSRA, sample project)

Another benefit of the P'IA is the ability to produce probabilistic cash flow graphs (Figure 19). This can be of great assistance in monitoring and controlling of a project (Barraza, Back, & Mata, 2000).

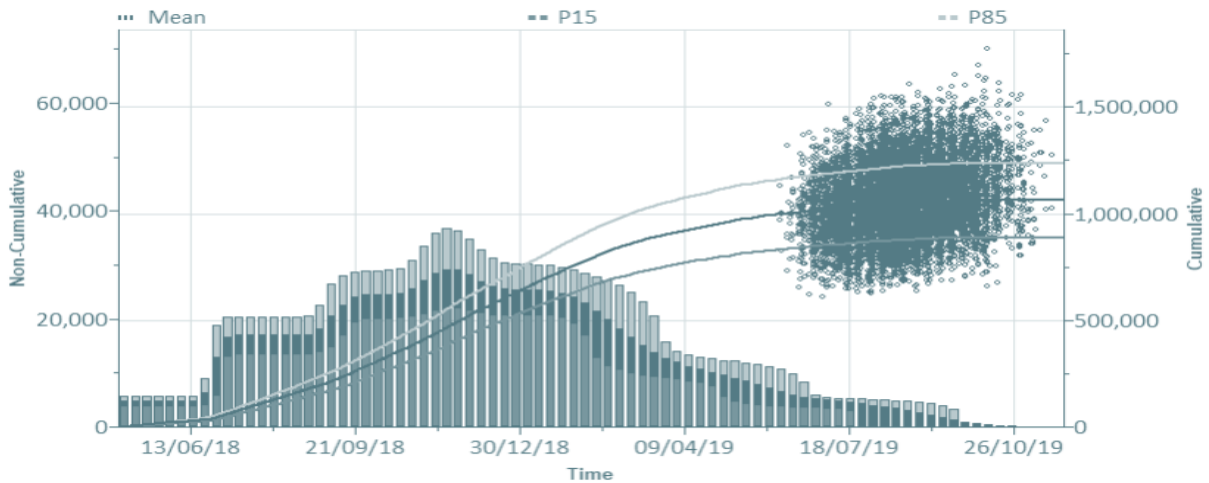


Figure 19: Probabilistic cash flow graph (P'ICSRA, sample project)

3 CASE STUDY

In this chapter, first the rationale for selecting the specific project is explained. Then a very basic description of the project is given. The approach that was followed by the company is then identified and the risk analysis procedures that the company applied are described. Last, special considerations regarding the application of the P'SA and P'IA are explained.

3.1 PROJECT SELECTION

Early in the research it was identified that the company followed a form of SA for risk analysis on their projects. The SA followed by the company is not the same as the P'SA, described in the previous chapter. The C'SA includes three separate analyses, two dedicated to cost and one to schedule, whilst the P'SA includes two analyses, one for each variable.

As described in paragraph 1.5, the purpose of the case study in this research is twofold. First, to reveal the details of the C'SA and the procedures that the company followed for the specific project. It will then be possible to understand the differences from the P'SA, developed through literature research, and put the company's results into perspective. Second, to collect data regarding the uncertainties and parameters that were originally used. It will then be possible to reuse the same information in the implementation of the P'SA and P'IA. Having said that, project information is not blindly copied as inputs to the new analyses. The goal is that the new analyses are performed correctly, as identified in literature and guidelines. Data that would produce poor inputs may compromise the analyses. Therefore, whenever deemed necessary, inputs were based on literature or expert opinion to preserve the integrity of the analyses. The same principle applied when information was not available from the company's analyses.

To achieve the goals of the case study, and of the research in general, the following requirements were set for the selection of the project to be investigated:

1. Both of company's cost related risk analyses (C'CRA-1 and C'CRA-2) performed.
2. Company's schedule risk analysis (C'SRA) performed.
3. End of project results for schedule and cost available.

Finding a project to comply to these requirements proved to be a challenging task for two reasons. First, not all three risk procedures are implemented in every project. Depending on the nature of the project some of the procedures may be regarded as superfluous and therefore omitted. Parameters like contract type, risk allocation, project size will affect the choice of procedures to be performed. Second, the C'SRA is a relatively new procedure within the company. Consequently, not many projects existed that fulfilled requirements 2 and 3, because generally projects complying to requirement 2, were still in progress.

3.2 PROJECT DESCRIPTION

The selected project concerns the EPC phase of a chemical plant. The contract between the main contractor and the client was of reimbursable type and commenced in 2012. Within the chemical plant, four major units are identified that can be regarded as stand-alone subprojects. Activities for these subprojects were scheduled in parallel. Similarly, Engineering, Procurement and Construction phases were scheduled as concurrent.

3.3 COMPANY'S SEPARATED APPROACH (C'SA)

As mentioned above, three risk analyses are performed by the company. These analyses in principle are first conducted before submitting binding offer documents in order to submit realistic estimates to the client. Later, they are carried out periodically in predetermined time intervals or when necessary, to assist in monitoring and controlling the progress of the project. In all the original analyses carried out on this case study project, an 85% confidence level was considered as acceptable.

3.3.1 COMPANY'S FIRST COST RISK ANALYSIS (C'CRA-1)

The C'CRA-1 is an analysis performed to determine the cost contingency required to account for the existence of risk events with impacts on the cost side of the project. The procedure followed for this analysis is shown in Figure 20 (placed over the P'CRA procedure). In this analysis, only risk events are entered, and their impacts are not assigned to specific cost elements. Therefore, the latter are not required for the analysis. As a result, the risk register itself constitutes the model on which the MC analysis is performed. A cost distribution is then generated. Given the desired confidence level, the corresponding cost contingency is pinpointed on the distribution graph. This analysis was performed using a company's in-house software solution.

A few important notes on the implementation of this analysis follow. Even though a risk event ranking could also be derived from the MC analysis, in the specific implementation of this analysis on the case study project it was not. Additionally, before the contract award, there was no C'CRA-1 performed. Only a few months after the project start, the first C'CRA-1 was performed. Therefore, in the initial cost estimate of the project, the C'CRA-1 did not contribute to the determining the cost contingency amount. As a result, the project cost contingency was determined exclusively from the C'CRA-2 that follows. Of course, a qualitative risk analysis was performed before bidding where the risk events were identified and qualitatively assessed. Finally, only risks that could potentially affect the profitability of the company were included in the risk register. Because the contract type was reimbursable, these risk events were limited in number.

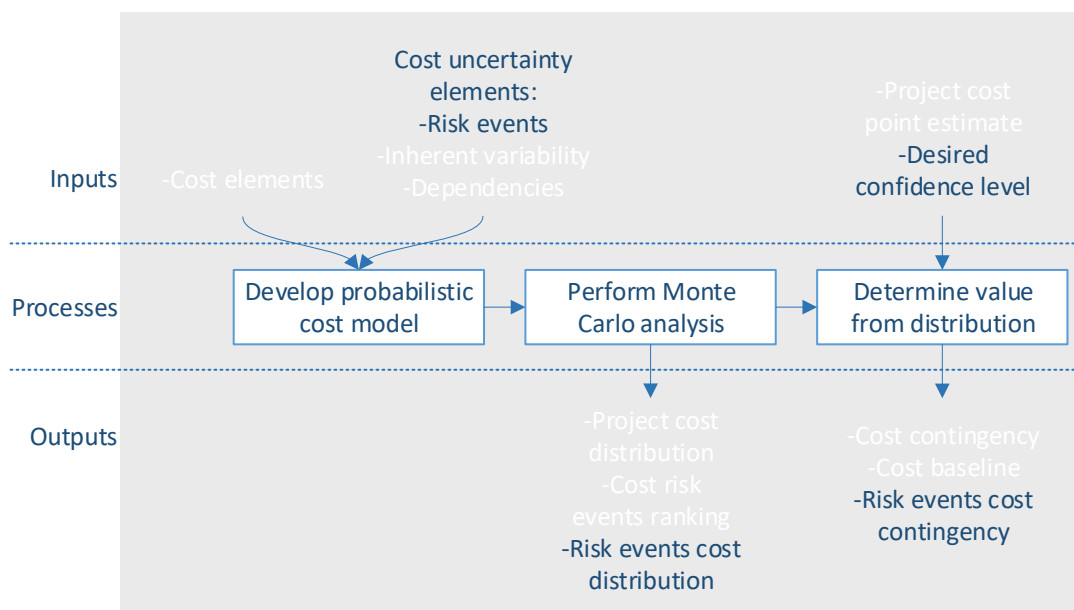


Figure 20: Company's first Cost Risk Analysis (C'CRA-1) procedure

3.3.2 COMPANY'S SECOND COST RISK ANALYSIS (C'CRA-2)

The C'CRA-2 is an analysis performed to determine the cost contingency required to account for the existence of inherent variability on the cost elements of a project. The procedure followed for this analysis is shown in Figure 21. Contrary to C'CRA-1, cost elements are required and entered in this analysis. These elements are defined on a relatively high level. Specifically, each cost element is a summation of the partial cost elements from the respective sub-projects. Inherent variability is then assigned where necessary on these "summary" cost elements to create the probabilistic model, which has a spreadsheet form. Risk events and correlations are omitted from this analysis. Through a MC simulation the cost distribution is generated, and the cost contingency amount is determined, given the desired confidence level. The cost contingency analysis was performed right before the cost estimate was issued to the client and its outcome determined the contingency that was added to the deterministic cost. This analysis was performed using Palisade's @Risk in interaction with Microsoft's Excel.

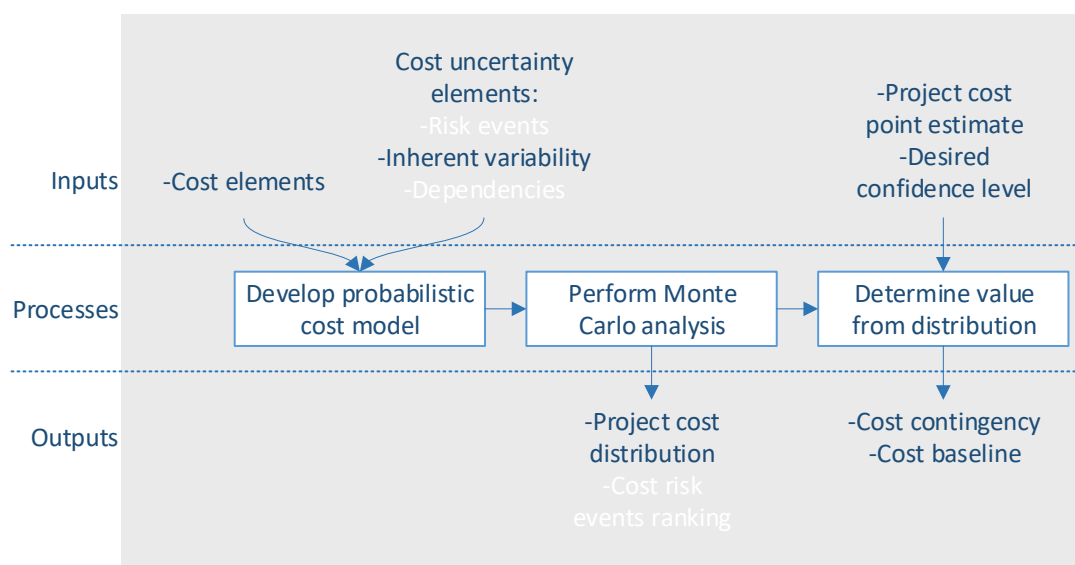


Figure 21: Company's second Cost Risk Analysis (C'CRA-2) procedure

3.3.3 COMPANY'S SCHEDULE RISK ANALYSIS (C'SRA)

C'SRA is an analysis performed to determine the contingency required to account for the existence of risk events with impacts on the schedule side of the project. The procedure followed for this analysis is shown in Figure 22. This procedure is similar to the P'SRA procedure from the P'SA, described earlier. The difference is that inherent variability and correlations are ignored. Therefore, only risk events are assigned to the schedule model. Project duration distribution and prioritized risk event register are then generated from the MC simulations and the contingency can then be determined for a certain confidence level. This analysis was performed using Oracle's Primavera Risk Analysis software solution.

At the time of the contract award two schedule risk analyses were performed. One using a summary schedule and one using a more detailed. In literature, both approaches are considered appropriate with their own pros and cons (Caddell et al., 2012). Mutual for both analyses is the fact they were performed on schedule models that included only part of the project scope (1 or 2 of the sub-projects). The reasoning was that only the activities for these subprojects were considered to be on the critical or near-critical paths.

This is a common practice when performing SRA. By decreasing the number of activities and paths, the overview and manageability of the network logic is improved, and the SRA is simplified. It is however

important not to neglect network paths that can potentially become critical in case they are subjected to increased uncertainty. If they are omitted, the project duration distribution will be impacted and show a more optimistic result. It is essential then, that all near-critical paths with the potential to affect the distribution of the project duration, are included (Caddell et al., 2012).

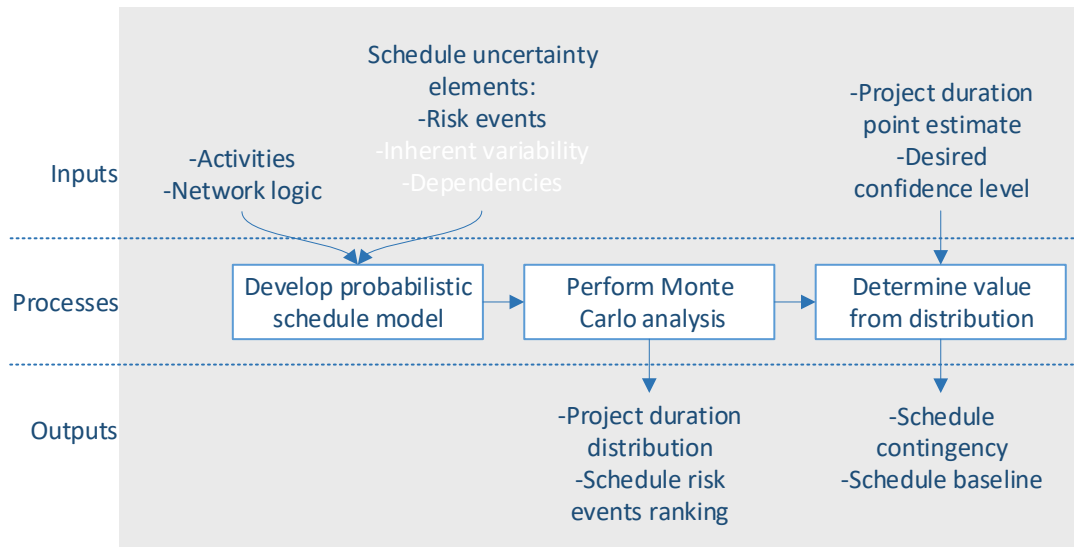


Figure 22: Company's Schedule Risk Analysis (C'SRA) procedure

3.4 CONSIDERATIONS FOR PROPOSED APPROACHES

As already mentioned the goal is to reuse the same information, to the extent that is possible, for the application of the P'SA and P'IA, presented in paragraphs 2.5.1 and 2.5.2. However, the company's analyses, had several omissions compared to the proposed ones. Therefore, to apply the P'SA and P'IA optimally, without compromising their quality, modifications on the original models and new assumptions were necessary. All the proposed analyses were conducted using Oracle's Primavera Risk Analysis in interaction with Oracle's Primavera P6 Professional 17.

3.4.1 PROPOSED COST RISK ANALYSIS (P'CRA)

For this analysis, data from C'CRA-1 and C'CRA-2 are reused. But some modifications are made to improve the quality of the analysis. Specifically, a more detailed model is used. The "summary" cost elements, used in the C'CRA-2, are deconstructed to reveal the comprising elements that refer to specific sub-projects. Specifically, the C'CRA-2 is composed of around 25 summary resources, while the P'CRA is composed of 86 "less summarized" resources. This change improves the detail and quality of the risk analysis. Also, it aligns the cost model with the schedule model to prepare for the integration that will take place during the P'IA.

Uncertainty elements are then assigned to these lower-level cost elements. Specifically, parameters for risk events are taken from the C'CRA-1, parameters for inherent variability are taken from C'CRA-2 and correlation parameters are established based on guidelines and literature recommendations (Appendix 1).

3.4.2 PROPOSED SCHEDULE RISK ANALYSIS (P'SRA)

For this analysis, data from C'SRA are reused. The C'SRA was performed only on a portion of the project scope. Caddell et al. (2012) suggest that a good practice is to include the whole scope of the project in the schedule. Nevertheless, the intend would be to use the same schedule to make for a fairer comparison between the different analyses. While this would be possible in the P'SRA, it is not in the

P'IA, In the P'IA here is the requirement of having the whole scope in the schedule so that the complete cost of the project can be attached. In order to prepare the schedule for the integration that is explained later, a new schedule with the full scope reflected was preferred. However, the only schedules available, that had the full-scope of the project incorporated, were very detailed and not “ready” for risk analysis. Nevertheless, a schedule created at the same period as the cost estimations (just before bidding proposal), was selected and modified according to good schedule risk analysis practices (Caddell et al., 2012).

First the number of activities was reduced considerably, from approximately 2500 to 1300. This was achieved by merging series of activities that described consecutive tasks and by deleting activities that were considered superfluous (very detailed, no risks to be attached, no costs to be attached). All modifications were performed without altering schedule logic. The reduction of the schedule size does not weaken the quality of the risk analysis. An overly detailed schedule does not provide additional value to a risk analysis. Conversely it makes the analysis more cumbersome and the results more difficult to interpret. Also, the bigger the schedule the more prone to the “Central Limit Theorem” phenomenon as explained in Appendix 1. In short, because of the “Central Limit Theorem”, the final distribution tends to be narrower, the larger the number of activities in a schedule.

Another important modification was the removal of unnecessary constraints. The industry recommendation is to refrain from using constraints when developing schedule. However, in practice constraints are used in abundance, and most of them indicate preferences rather than actual schedule constraints (Caddell et al., 2012). While this practice is suboptimal for regular planning purposes, for a schedule risk analysis it is catastrophic. That is because constraints will restrict the start or finish of activities and therefore cancel any variation introduced by the uncertainties. This takes away the essence of a SRA, which is to simulate the effects of uncertainty on the schedule. The detailed schedule selected for the analysis had several constraints attached. Therefore, all the constraints were examined and those considered more of expressing preferences rather than “real” constraints were stripped off.

In the C'SRA, only risk events were included. Parameters for this uncertainty type are transferred to the P'SRA. Parameters for inherent variability were derived from other projects in the organization where this uncertainty element was considered and incorporated in their respective C'SRAs. However, no data for correlations were available in the company and therefore the parameters are derived based on guidelines and literature recommendations as shown in Appendix 1

3.4.3 PROPOSED INTEGRATED COST AND SCHEDULE RISK ANALYSIS (P'ICSRA)

Before the integration of schedule and cost risk analyses can be performed, several preconditions must be met. The schedule should represent the whole scope of the project. The integration materializes by assigning costs or resources to activities. It is essential then that the whole scope of the project is represented in the schedule, so that the total cost can be properly represented as well. As mentioned, a proper full-scope schedule model is prepared during the P'SRA. This schedule is reused in the P'ICSRA. However, in the C'SA the teams responsible for scheduling and cost estimating are developing their models independently of each other. Subsequently, cost elements may not have corresponding schedule activities assigned. Or the granularity level of the cost elements may be different than of the schedule activities. These issues are resolved in this analysis before the integration of schedule and cost is undertaken.

Specifically, there were 1381 activities in the schedule model and 86 resources in the cost model. The resources were structured more according to disciplines while the activities were strict to the work packages. Obviously a one to one relation did not exist. To overcome this obstacle, summary activities were created to reflect the structure of the cost model. The resources could then be assigned to the

corresponding summary activities. Under the summary activities, regular activities were positioned that had a partial contribution to the corresponding resource. This was performed without altering the logic of the schedule. By doing this the duration of the summary activity was enabled to fluctuate according to the durations' fluctuations of the underlying activities.

The duration fluctuation of the summary activity can now influence the TD resources assigned to it. Of course, for that to simulate properly, the cost elements or resources need to be classified either as TD or as TI. The classification of some cost elements could be easily inferred by their type (labor or material). Some cost elements however consisted of a mix of TD and TI resources. For such cost elements, the ratio of the two was determined by experts' advice within the company. In this project, direct costs include items like labor, material, subcontracts, and thus are described by a mix of TD and TI cost elements. Indirect elements on the other hand, include items like project management and temporary facilities and are predominantly classified as TD. Regarding the uncertainty elements required for the analysis in the P'IA, they were all available from the analyses in the P'SA.

3.5 PROJECT RESULTS

During the project, cost and time quantities are tracked to monitor the progress and plan the management approach. At project completion, the final values for these quantities are revealed and an assessment can be made on their performance. The first thought would be to compare the actual cost and finish date of the project with the cost and finish date values derived from the analyses' respective distributions for selected confidence levels. This however, would ignore the fact that projects are live organizations that evolve over time. The scope at the time of a project's completion has the potential to differ substantially from the scope at the time of the project's start (Willems & Vanhoucke, 2015).

In general, provisions for major scope changes are not regarded when calculating the contingency reserves. In this project, contingency calculation follows the same principle. This is clearly depicted in the following quote, retrieved from a project document where cost contingency is defined as:

"a special monetary provision in the project budget to cover uncertainties or unforeseeable elements of time/cost within the scope of the project under the company's control. Contingency typically covers risk of cost increases resulting from lack of scope definition, lack of particular experience, omissions, underestimation, technical problems, nonspecific schedule slippage, and like items. Major Scope changes are explicitly excluded from contingency, and considered a client's cost."

To summarize, cost distributions from the analyses encompass only cost contingency reserves, which exclude scope changes, whereas actual cost outcomes of the project are exposed to scope changes as well. It becomes clear that cost distributions from the analyses and actual project costs describe different notions. Consequently, a direct comparison of the actual total cost of the project against cost values derived from the analyses' cost distributions may be misleading and ignore important project realities.

To avoid this shortcoming and compare like for like, the progress of the project and more specifically the evolution of the total cost was tracked through the monthly cost reports. These reports systematically record the monetary progress of the project in a very comprehensive manner and classify any cost development as either a change order or a cost contingency amount. The identified consumed cost contingency during the project constitutes a proper reference against which the contingencies from the different analyses can be compared and assessed.

A similar process could not be followed for the schedule quantities. Schedule evolution during the project is not recorded and reported as thoroughly as cost development is. Subsequently, schedule

delays belonging to the schedule contingency category could not be distinguished from schedule delays caused by other factors including scope changes. A very simple rule of thumb is to adopt the ‘contingency to change orders’ ratio from the cost results. This entails the assumption that cost development during the project is proportional to schedule development, something that does not necessarily apply. In other words, a 1% increase in project costs does not come with 1% increase in project duration. Nevertheless, without any better alternative, this assumption is adopted.

3.6 UNCERTAINTY ELEMENTS SYNOPSIS

Table 11 provides a concise overview about which uncertainty elements are included in each analysis

Table 11: Uncertainty elements included in analyses

		Cost uncertainty elements			Schedule uncertainty elements		
		Inherent variability	Risk events	Correlation	Inherent variability	Risk events	Correlation
C'SA	C'CRA-1	—	+	—	—	—	—
	C'CRA-2	+	—	—	—	—	—
	C'SRA	—	—	—	—	+	—
P'SA	P'CRA	+	+	+	—	—	—
	P'SRA	—	—	—	+	+	+
P'IA	P'ICSRA	+	+	+	+	+	+

3.7 OUTCOMES SYNOPSIS

Because of the different inputs and processes used in the introduced risk analyses, different outcomes are possible from each analysis as well. Table 12 shows what outcomes are produced from each analysis.

Table 12: Outcomes available from analyses and at project completion

		Outcomes					
		Cost contingency	Schedule contingency	Cost risk events ranking	Schedule risk events ranking	Joint confidence level	Probabilistic cash flow
C'SA	C'CRA-1	+	—	—	—	—	—
	C'CRA-2	+	—	—	—	—	—
	C'SRA	—	+	—	—	—	—
P'SA	P'CRA	+	—	+	—	—	—
	P'SRA	—	+	—	+	—	—
P'IA	P'ICSRA	+	+	+	+	+	+

4 RESULTS

The analyses described so far are implemented in the case study project. As presented in Table 12, specific outcomes are obtainable from each analysis. In this chapter, the results of the outcomes are presented and supplemented with notable observations, in the same order that the analyses are listed in Table 12. At the end, the actual outcomes of the project are identified and presented.

4.1 COMPANY'S FIRST COST RISK ANALYSIS (C'CRA-1)

Figure 23 shows the density and cumulative distributions generated by the C'CRA-1. Contrary to the distributions from all the other analyses, this distribution directly shows the contingency amount that should be accounted for the existence of risk events. This is because cost elements are absent from this analysis and therefore the distribution depicts solely contingency, without any deterministic cost added. This is further illustrated in Figure 20, where the project deterministic cost estimate is not required as an input for this analysis. Even though uncertainty produced from risk events should be part of total cost contingency calculation, in this project it was not.

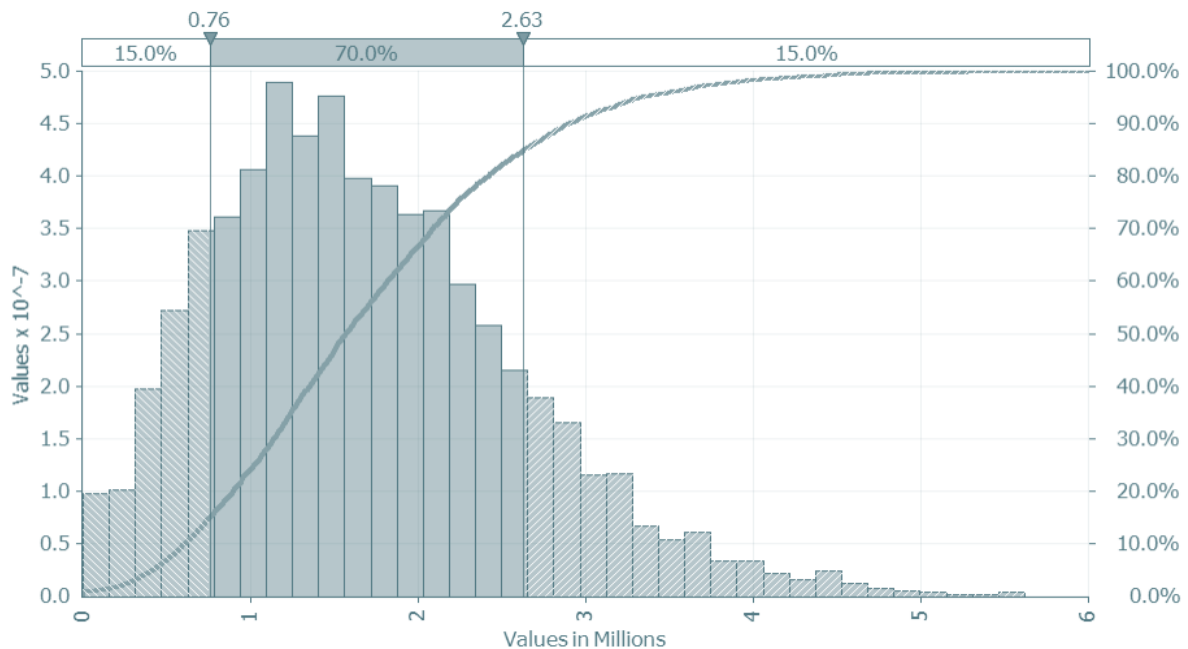


Figure 23: Cost distributions (C'CRA-1)

For an 85% confidence level the required contingency to account for the existence of risk events is 2.63 million as shown in Table 13.

Table 13: Basic statistics and cost contingency amount (C'CRA-1)

Measure	Value
Minimum value	0€ million
Mean value	1.69€ million
Median value	1.57€ million
Maximum value	5.62€ million
Standard deviation	0.91€ million
Corresponding cost for an 85% confidence level	2.63€ million

4.2 COMPANY'S SECOND COST RISK ANALYSIS (C'CRA-2)

The graph in Figure 24 shows the cost distribution generated from the C'CRA-2. The "rough" outline of the distribution is a consequence of the low number of MC iterations.

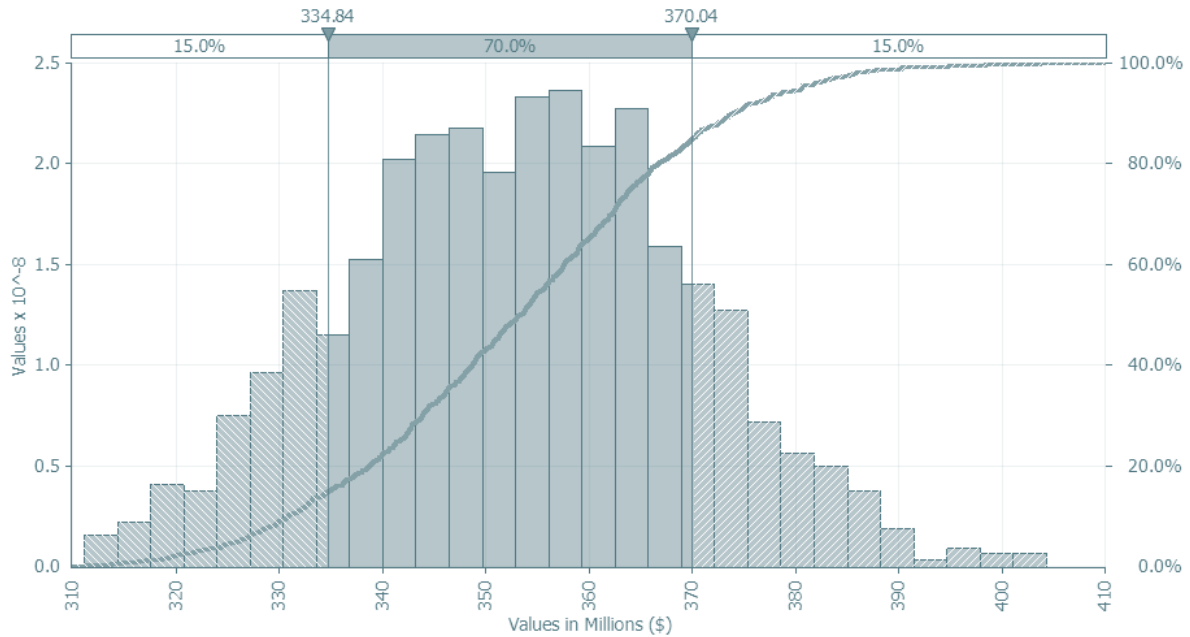


Figure 24: Cost distributions (C'CRA-2)

As shown in Table 14, the probability of not exceeding the deterministic cost estimate of 348€ million is 39%. If an 85% confidence level is pursued, then the cost estimate should be set at approximately 370€ million. The 22€ million difference between the deterministic and probabilistic estimates resembles the contingency amount that should be added to reach the desired confidence level.

Table 14: Basic statistics and cost contingency amount (C'CRA-2)

Measure	Value
Minimum value	311€ million
Mean value	353€ million
Median value	353€ million
Maximum value	404€ million
Standard deviation	16€ million
Corresponding confidence level for the deterministic cost estimate (348€ million)	39%
Corresponding probabilistic cost estimate for an 85% confidence level	370€ million
Required cost contingency for an 85% confidence level	22€ million

4.3 COMPANY'S SCHEDULE RISK ANALYSIS (C'SRA)

Figure 25 shows the finish date distribution³ from the C'SRA. The distribution does not have a smooth bell-shaped outline. The inclusion of only risk events, and the relatively low number of iterations for the

³ A duration distribution can also be obtained from the analysis. This distribution would be identical to the finish date one because the two variables are linearly dependent, e.g. they can be written as a linear function of the other. The finish date is merely the conversion of the duration into calendar units.

MC simulation played a part in this. The step at the left end of the distribution is caused because in many of the iterations, the shortest path in the network, which determines the finish date, ended up being the deterministic critical path, because no risk events occurred on that. That explains also why the minimum value from the simulation is the same as the deterministic date.

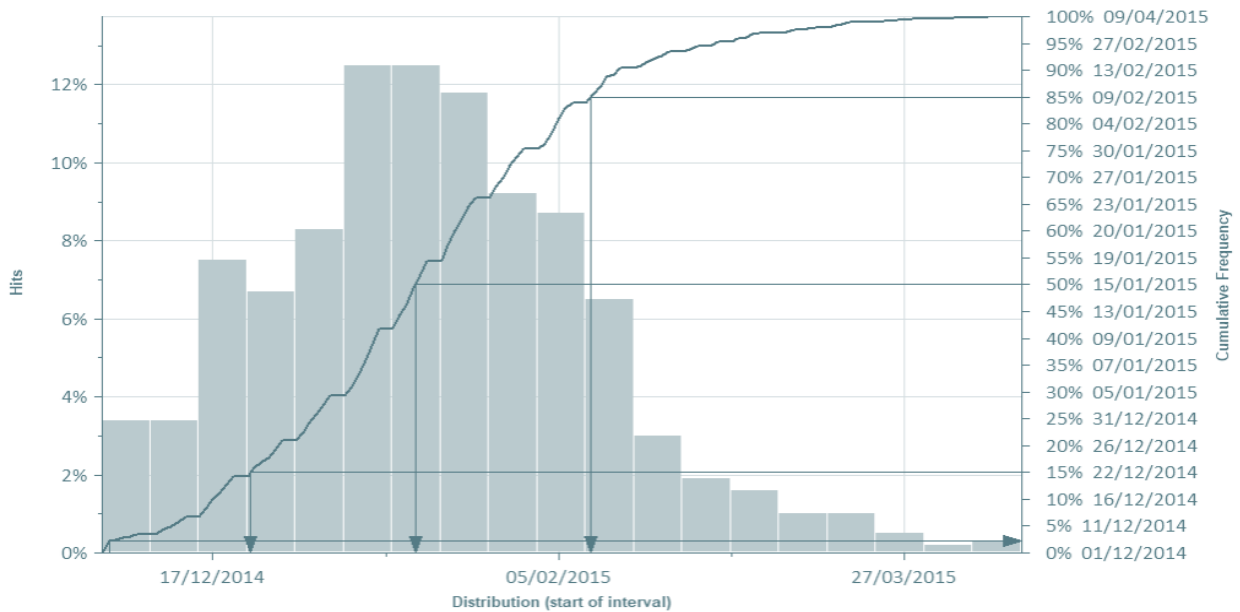


Figure 25: Finish date distributions (C'SRA)

As shown in Table 15, the probability of not exceeding the deterministic finish date (01/12/2014) is 2%. If an 85% confidence level is pursued, then the finish date should be set for 09/02/2015. The resulting contingency is calculated to 70 days.

Table 15: Basic statistics and schedule contingency amount (C'SRA)

Measure	Value
Minimum value	01/12/2014
Mean value	16/01/2015
Median value	15/01/2015
Maximum value	09/04/2015
Standard deviation	23 days
Corresponding confidence level for the deterministic finish date (1/12/2014)	2%
Corresponding finish date for an 85% confidence level	09/02/2015
Required duration contingency for an 85% confidence level	70 days

4.4 PROPOSED COST RISK ANALYSIS (P'CRA)

Figure 26 shows the distribution of total costs for the P'CRA.

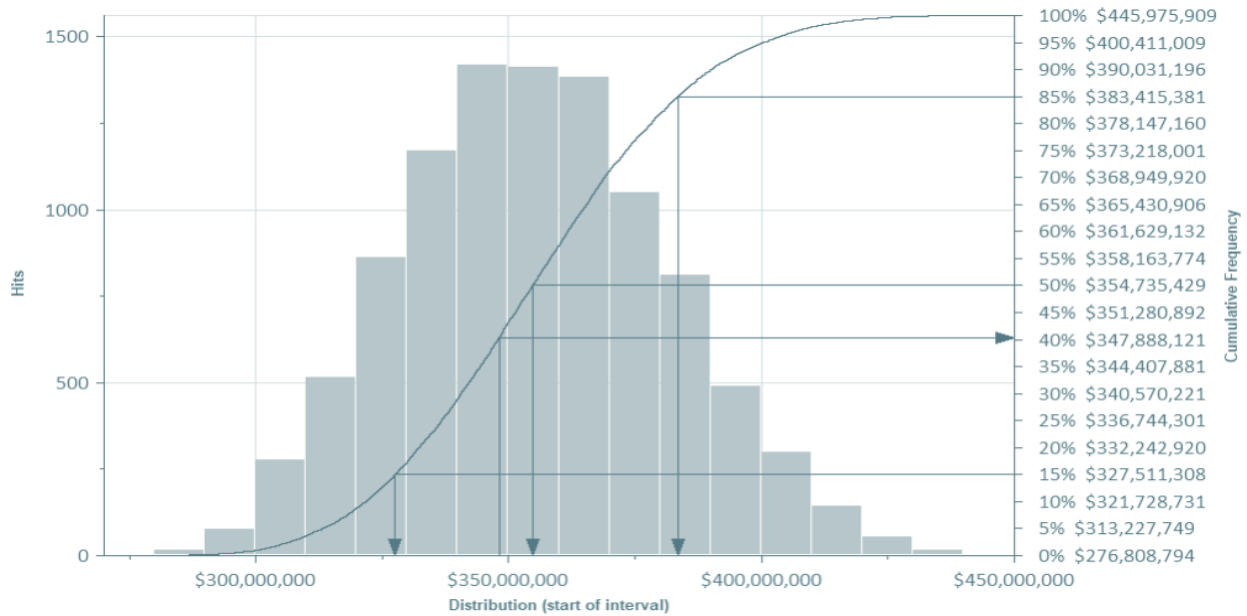


Figure 26: Cost distributions (P'CRA)

The probability of not exceeding the deterministic cost estimate of 348€ million is 40%. If an 85% confidence level is pursued, then the cost estimate should be set at approximately 383€ million. The needed cost contingency is therefore 35€ million.

Table 16: Basic statistics and cost contingency amount (P'CRA)

Measure	Value
Minimum value	277€ million
Mean value	355€ million
Median value	355€ million
Maximum value	446€ million
Standard deviation	26€ million
Corresponding confidence level for the deterministic cost (348€ million)	40%
Corresponding cost for an 85% confidence level	383€ million
Required contingency amount for an 85% confidence level	35€ million

Figure 27 shows the cost risk event ranking generated by this analysis. The ranking is based on the correlation between the occurrence of a risk event and the cost of the project. In principle, the higher the contribution of a risk event to the variance of the cost, the higher the correlation.

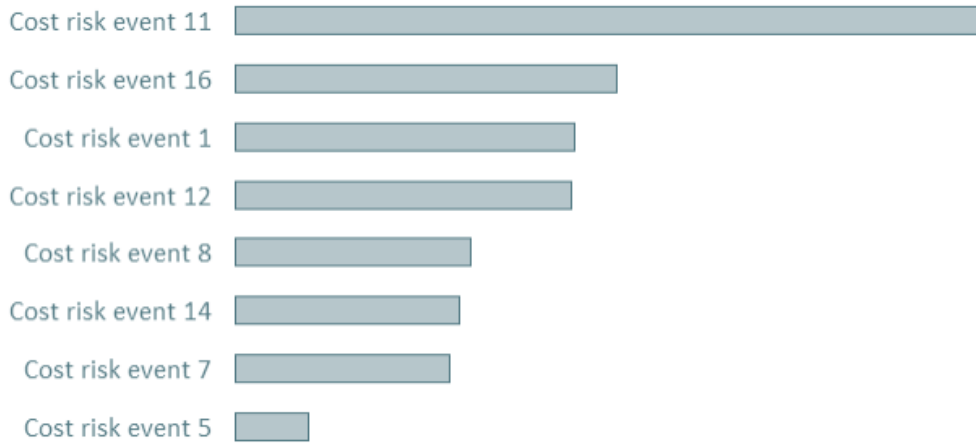


Figure 27: Cost risk event ranking (P'CRA)

4.5 PROPOSED SCHEDULE RISK ANALYSIS (P'SRA)

The graph in Figure 28 shows the resulting finish date distribution of the P'SRA. Contrary to the distribution from the C'SRA, there is no step at the left side of the distribution because of the inclusion of inherent variability, and for the same reason the outline is smoother.

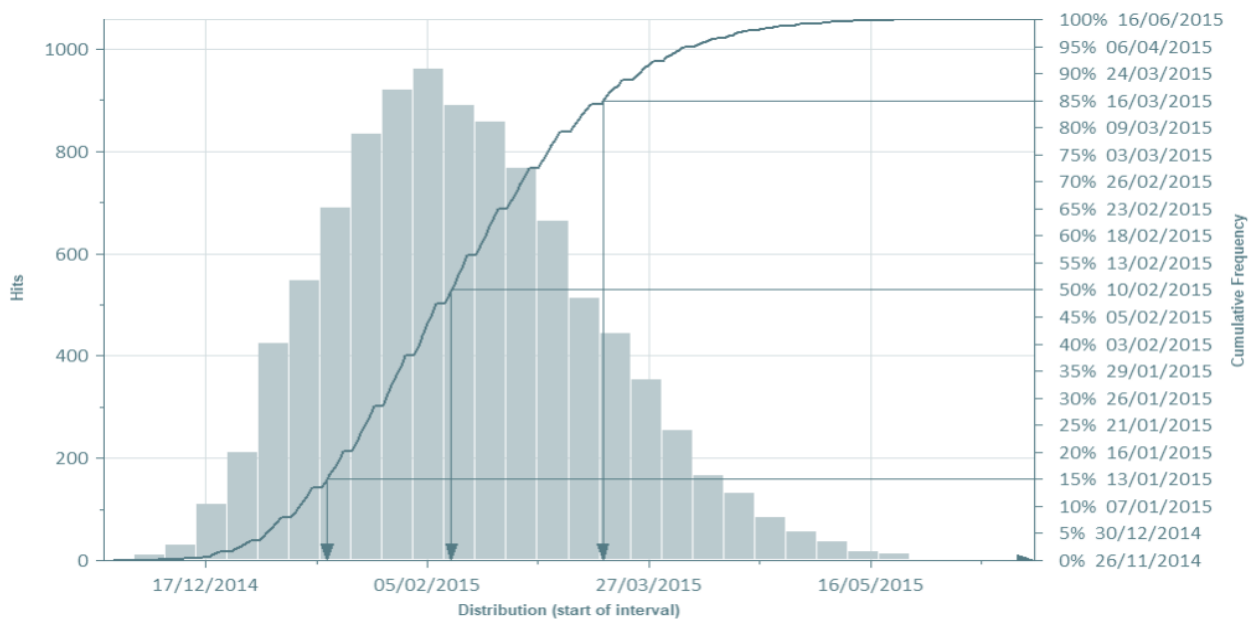


Figure 28: Finish date distributions (P'SRA)

The probability of not exceeding the deterministic finish date (01/12/2014) is less than 1%. If an 85% confidence level is pursued, then the finish date should be set for 16/03/2015. This requires a schedule contingency of 105 days (Table 17).

Table 17: Basic statistics and schedule contingency amount (P'SRA)

Measure	Value
Minimum value	26/11/2014
Mean value	11/02/2015
Median value	10/02/2015
Maximum value	16/06/2015

Standard deviation	29 days
Corresponding confidence level for the deterministic finish date (1/12/2014)	<1%
Corresponding finish date for an 85% confidence level	16/03/2015
Required contingency amount for an 85% confidence level	105 days

Figure 29 shows the schedule risk event ranking from this analysis.

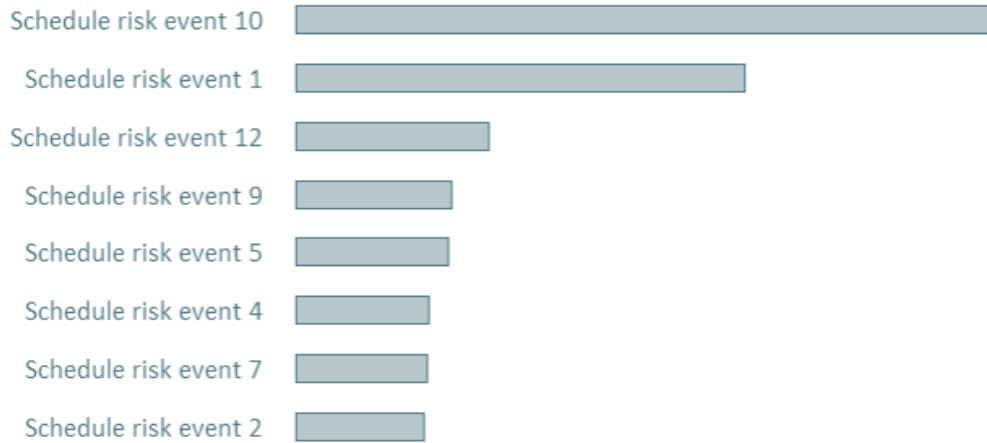


Figure 29: Schedule risk event ranking (P'SRA)

4.6 PROPOSED INTEGRATED COST AND SCHEDULE RISK ANALYSIS (P'ICSRA)

The resulting cost distribution from the P'ICSRA is shown in Figure 30.

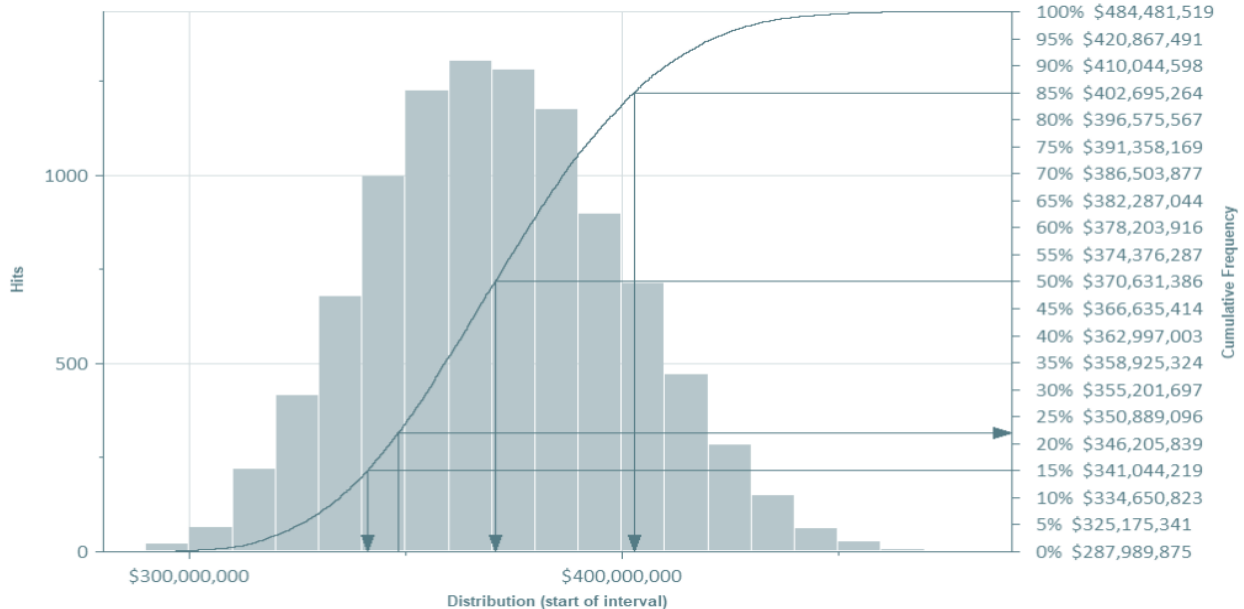


Figure 30: Cost distributions (P'ICSRA)

For the P'ICSRA, the probability of not exceeding the deterministic cost estimate is 22%. If an 85% confidence level is pursued, then the cost estimate should be set at approximately 403€ million. A 55€ million cost contingency is required to achieve the wanted certainty level (Table 18).

Table 18: Basic statistics and cost contingency amount (P'ICSRA)

Measure	Value
Minimum value	288€ million
Mean value	372€ million
Median value	371€ million
Maximum value	484€ million
Standard deviation	29€ million
Corresponding confidence level for the deterministic cost (348€ million)	22%
Corresponding cost for an 85% confidence level	403€ million
Required contingency amount for an 85% confidence level	55€ million

The resulting cost risk ranking is shown in Figure 31. Notably, all six higher ranked risk events were originally associated mainly with the schedule measure.

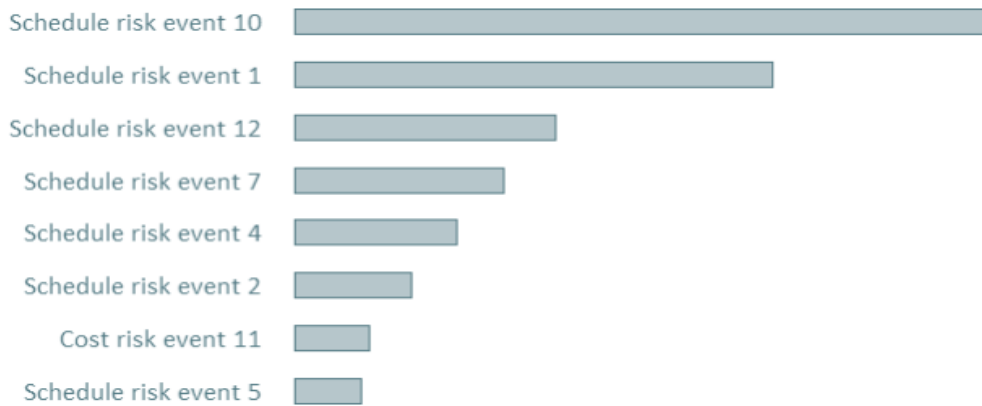


Figure 31: Cost risk events ranking (P'ICSRA)

Integration of schedule and cost affects only the cost related outcomes. As explained, schedule related uncertainties have an impact on duration which in turn affects the TD cost elements. Uncertainties on costs however, do not affect the duration in any way. As a result, for the schedule side of the P'ICSRA all the results are identical to the results generated by the P'SRA. Figure 32, Table 19 and Figure 33 are therefore identical to the figures in the P'SRA.

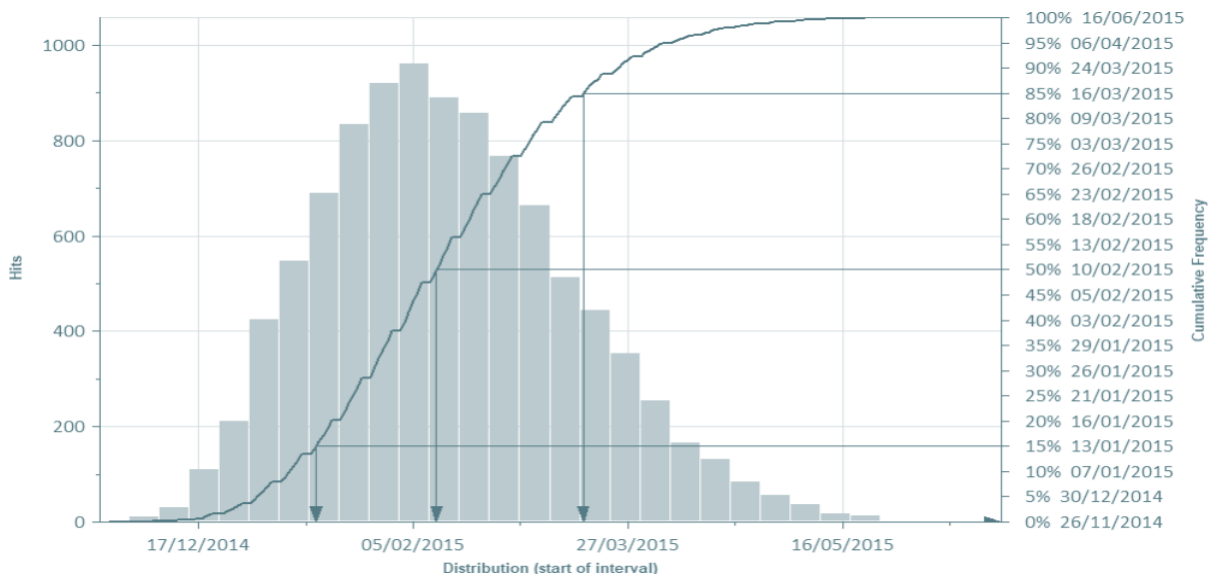


Figure 32: Finish date distributions (P'ICSRA)

Table 19: Basic statistics and schedule contingency amount (P'ICSRA)

Measure	Value
Minimum value	26/11/2014
Mean value	11/02/2015
Median value	10/02/2015
Maximum value	16/06/2015
Standard deviation	29 days
Corresponding confidence level for the deterministic finish date (1/12/2014)	<1%
Corresponding finish date for an 85% confidence level	16/03/2015
Required contingency amount for an 85% confidence level	105 days

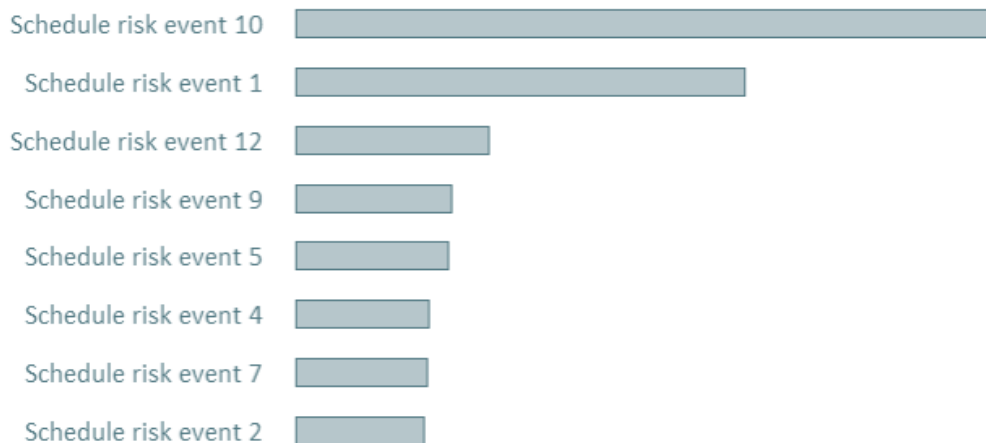


Figure 33: Schedule risk event ranking (P'ICSRA)

The P'IA provides the capability to generate outcomes that are impossible with the P'SA (Table 12). One outcome is the scatter plot, which shows the relationship between two output variables of a risk analysis. Particularly, each point on a scatter plot represents the output values of both variables (one on each axis) for a single iteration of the MC simulation. The totality of the iterations provides the sample from which the time-cost correlation and joint confidence level can be calculated. In this project time and cost ended up 26% positively correlated. This means that when the duration is longer, it is more likely that the costs will also be higher.

The big advantage however of having the scatter plot is the ability to calculate the joint confidence level (paragraph 2.5.2). The joint confidence level expresses the probability that a project's cost will be equal to or less than a specific value and that the finish date will be equal or earlier than a specific date. Figure 34 shows the resulting scatter plot in three different scenarios. In the top left, the highlighter bars are set to 85% marginal confidence level for time and cost. In this scenario the produced joint confidence level is 75%. In the top right plot, the joint confidence level is set to 85%. The highlighters cross on a single point in the plot, but all points on the blue line provide the same joint confidence level. At the bottom plot, the highlighters are set to the deterministic point (deterministic time and deterministic cost). The joint probability in this case is 0%.

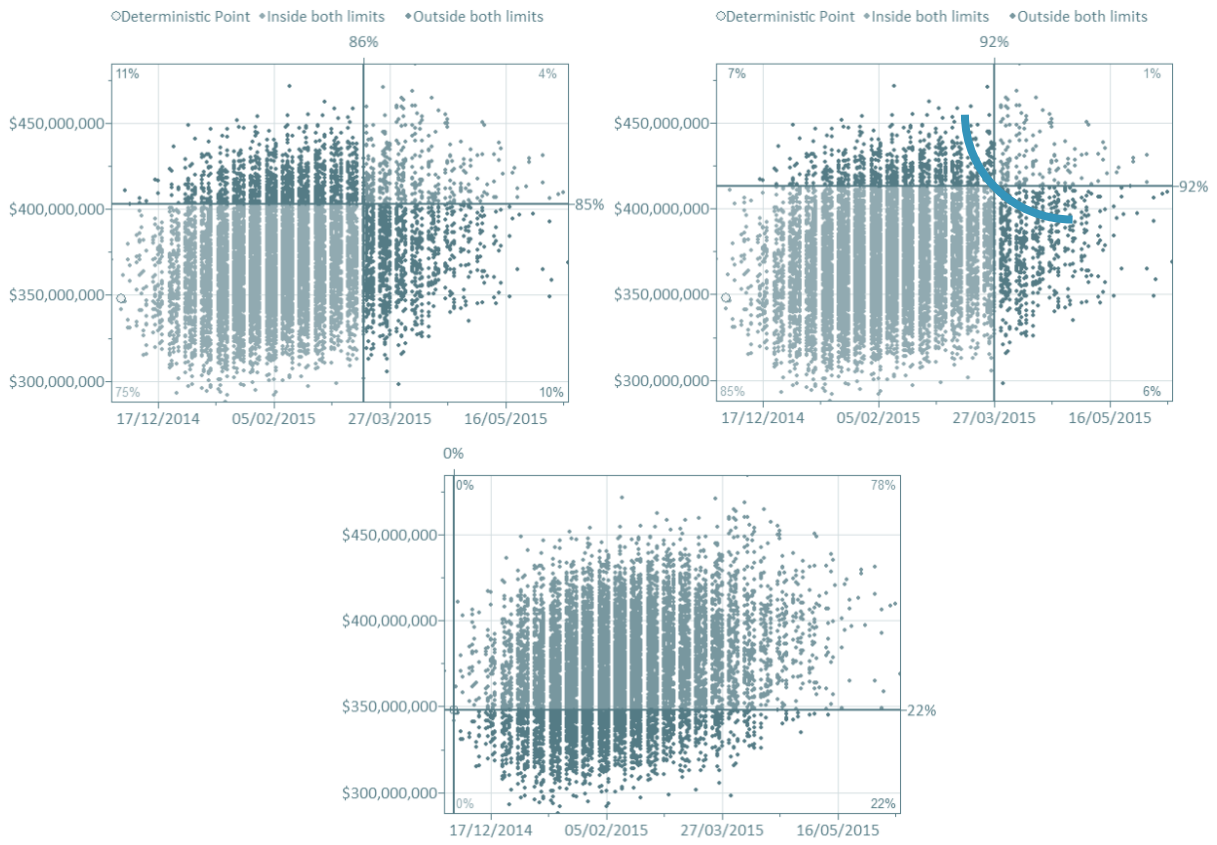


Figure 34: Scatter plots for different scenarios (P'ICSRA)

Table 20: Scatter plot results (P'ICSRA)

Measure	Value
Cost-time correlation (Pearson)	26%
Joint confidence level when individual confidence levels at set to 85%	75%
To achieve joint confidence level of 85%	Points located top-right of blue line
Joint confidence level for deterministic value	0%

Another outcome exclusive to the P'ICSRA is the probabilistic cash flow graph. This graph depicts the cash flow during the project for certain percentiles of certainty. In Figure 35 the probabilistic cash flow graph from the case study is displayed. The three lines represent the cash flow for an 85%, a 50% and an 15% confidence level (top to bottom). The accuracy of the graph depends on the correct assignment of the resources to their respective activities. This graph can be used during the project execution to overlay the actual cashflow and therefore detect deviations extending over the boundaries that the confidence level lines set and thus trigger actions to control the situation. This method provides an advanced way to monitor and control a project (Oracle Corporation, 2018). The point cluster at the top-right of the graph is the same as the scatter plots in Figure 34 showing the possible end states of the project realized by the simulation iterations.

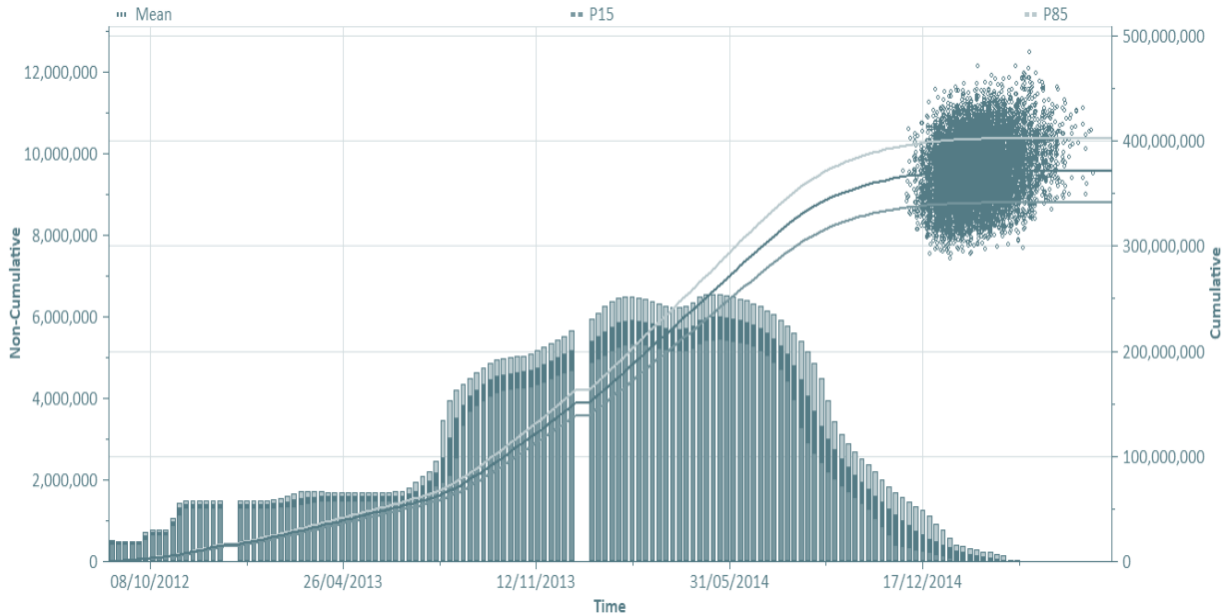


Figure 35: Probabilistic cash flow (P'ICSRA)

4.7 PROJECT OUTCOMES

As explained in paragraph 3.5, the cost contingency consumed during the project is identified to provide the reference against which the contingencies derived from the various analyses are compared. Also, based on the cost developments (contingency consumption and change orders), an improved cost forecast was developed in monthly intervals.

Cost forecast development is presented by the blue line in Figure 36. The final cost forecast should be, and it is, identical to the actual cost of the project because the project at that point is mostly completed, unknowns and uncertainties are negligible and therefore the forecast is essentially the real cost. From an initial cost estimate of approximately 370€ million (from C'CRA-2) the project ended up costing 670€ million. This is an increase of 81%. The difference between deterministic cost estimate and actual cost is 322€ million. Most of this difference is attributed to change orders, accumulating to 264€ million. The remaining cost increase of 58€ million was consumed as contingency.

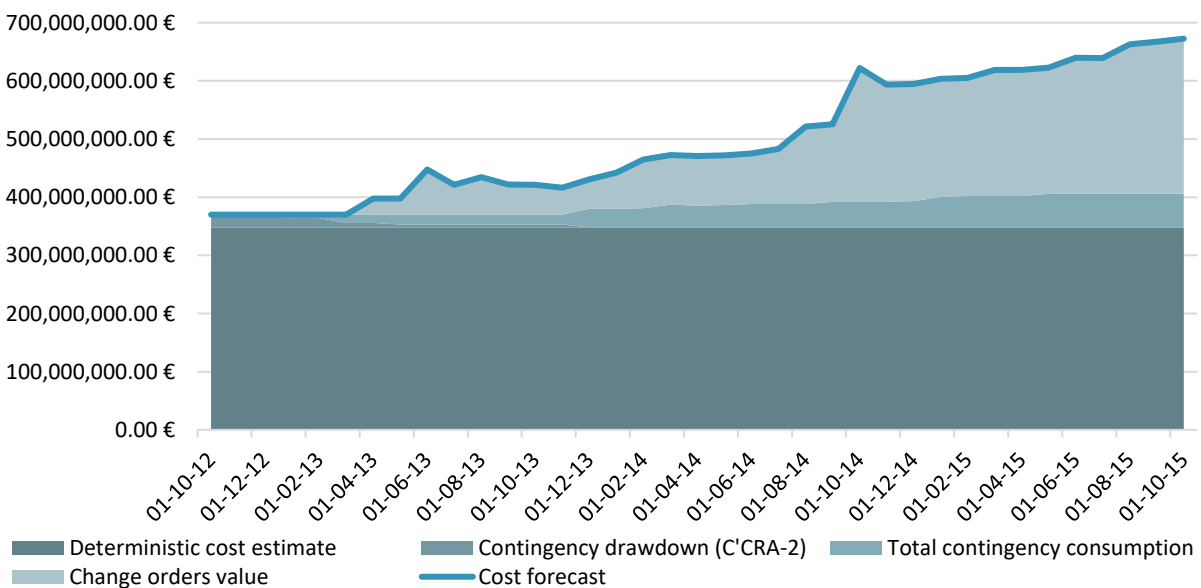


Figure 36: Cost composition throughout the project

The graph in Figure 37 provides a closer look at the contingency consumption during the project. The original contingency of 22€ million⁴ was completely consumed halfway through the project. Further 36€ million of contingency was consumed until the project completion.

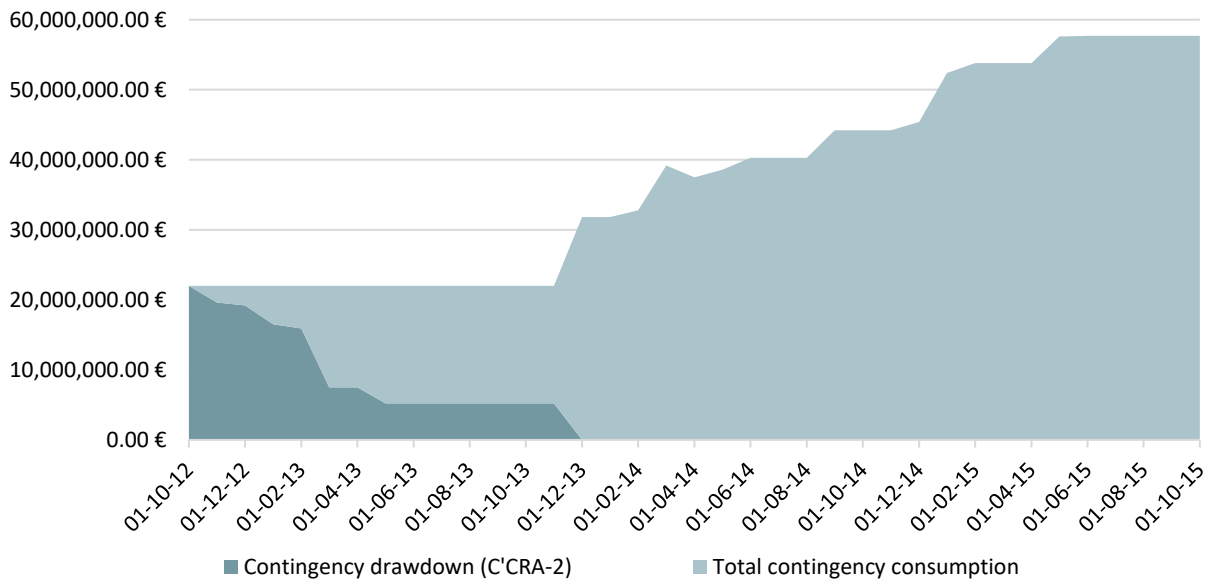


Figure 37: Contingency drawdown (C'CRA-2) and total contingency consumption throughout the project

Figure 38 shows the finish date estimate development during the project. The project eventually completed on 31/10/2015 compared to a deterministic finish date estimate of 01/12/2014, which amounts to 334 days of delay.

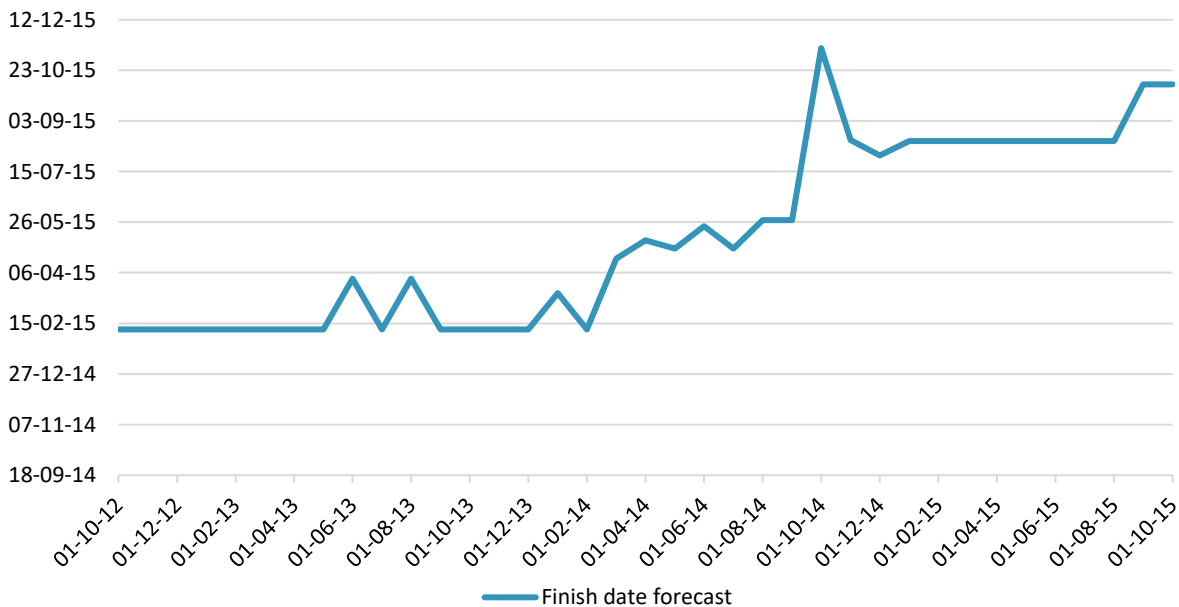


Figure 38: Finish date forecast throughout the project

As explained in paragraph 3.5, there is not enough information to derive the composition of the schedule developments from the project documentation and therefore a rule of thumb is applied. The

⁴ The finally adopted cost contingency amount was slightly different because of last minute alterations and discussions with the client, but the value derived from the C'CRA-2 (22 million) will be used as the basis as it makes for better reference to compare the different analyses

'contingency to change orders' ratio from the cost results is adopted for schedule. In this scenario, out of the 334 days of difference between deterministic finish date and actual finish date, 274 days would be the result of change orders while 60 days would be consumed as contingency.

5 RESULTS ANALYSIS & OBSERVATIONS

In this chapter, results from the different approaches will be analyzed and compared and important observations will be presented. Cost related outcomes will be analyzed first, followed by schedule related outcomes.

5.1 COST OUTCOMES ANALYSIS

Some key statistics, regarding the cost outcomes from the analyses, are compiled in Table 21.

Table 21: Key statistics for costs (all analyses)

Analysis	Mean cost value	Cost estimate at P85	Cost standard deviation	Probability of not exceeding the deterministic estimate
C'CRA-1	1.69€ million	2.63€ million	0.91€ million	N/A
C'CRA-2	353€ million	370€ million	16€ million	39%
P'CRA	355€ million	383€ million	26€ million	42%
P'ICSRA	372€ million	403€ million	29€ million	22%

The step from the C'CRA-2 to the P'CRA caused a negligible difference on the mean value of cost. This difference was mainly a result of the introduction of risk events (the 1.69€ million mean value from the C'CRA-1). Contrary, this step came with a big increase of the standard deviation of the cost distribution which can be attributed to the introduction of correlation. Correlation does exactly that; increases the variance and standard deviation of the distribution as explained in Appendix 1. In turn, the big difference in standard deviation between the two analyses causes a big difference of values at the extreme confidence levels at the outer edges of the distributions (Sander et al., 2016). Therefore, the value for an 85% confidence level, increased from 370€ million in the C'CRA-2 to 383€ million in the P'CRA, whereas the confidence level for the deterministic value, which is very close to the mean value, changed only by 3%.

Contrary to the previous step, the step from the P'CRA to the P'ICSRA has more of an impact on the mean value rather than the standard deviation of the cost distribution. To further analyze the results of the P'ICSRA and investigate the contribution of schedule uncertainties on the cost outcome, two special analyses were performed on the integrated model. One with only the schedule uncertainties enabled and one with only the cost uncertainties enabled. The resulting cost distributions are presented in the graph in Figure 39, and the key statistics are compiled in Table 22.

Table 22: Key statistics for costs (special P'ICSRA)

Analysis	Mean cost value	Cost estimate at P85	Cost standard deviation	Probability of not exceeding the deterministic estimate
P'ICSRA including only cost uncertainties	355€ million	383€ million	26€ million	40%
P'ICSRA including only schedule uncertainties	366€ million	374€ million	8€ million	<1%

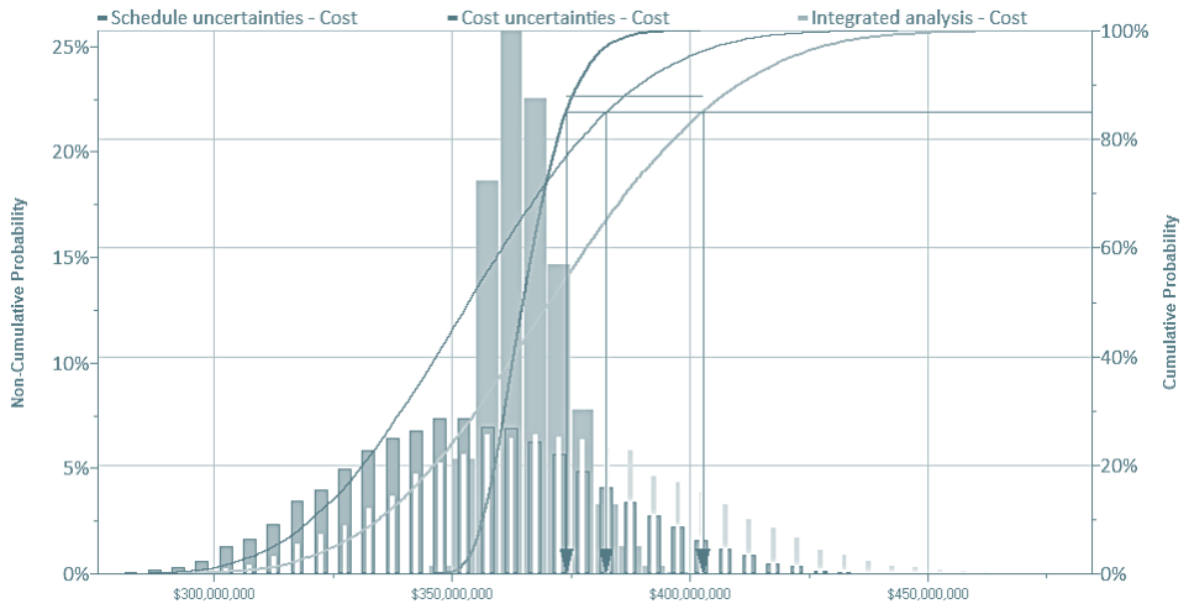


Figure 39: Cost distributions (special P'ICSRA)

The results from the P'ICSRA with only the cost uncertainty elements enabled (thinnest bars), are identical to the results of the P'CRA, as expected, because the uncertainty elements used in both analyses are the same. This can be easily conceptualized when looking at the matrix in Table 11. If the schedule uncertainty elements are removed from the P'ICSRA, it will replicate the P'CRA.

The cost distribution of the P'ICSRA with only schedule uncertainties enabled (thickest bars), has a relatively low standard deviation value, thus the very narrow shape. The rationale for this is that schedule uncertainties, in contrast with cost uncertainties, influence only the TD resources which constitute only part of the total costs. Particularly for this project, the deterministic cost of the TD resources was calculated to be 185€ million and of the TI resources to be 163€ million. As a result, in the P'ICSRA with only schedule uncertainties enabled, the 53% of the total costs can vary, while the 47% remains fixed. That is why the standard deviation is a lot lower compared to the standard deviation of the respective cost distribution from the P'ICSRA with only cost uncertainties enabled. And this is the reason why the step from the P'CRA to the P'ICSRA does not produce a considerable increase in standard deviation.

The increase of the mean value of the cost distribution, when moving from the P'CRA to the P'ICSRA, is now explained. The cost distribution of the P'ICSRA with only schedule uncertainties enabled has a mean value of 366€ million compared to 355€ million for the cost distribution of the P'ICSRA with only cost uncertainties enabled. Therefore, the convolution of the two probability distributions, that takes place in the P'ICSRA, produces the resulting probability distribution for costs (medium width bars), which has an increased mean value. The shift of the cost distribution is displayed more clearly in Figure 40.

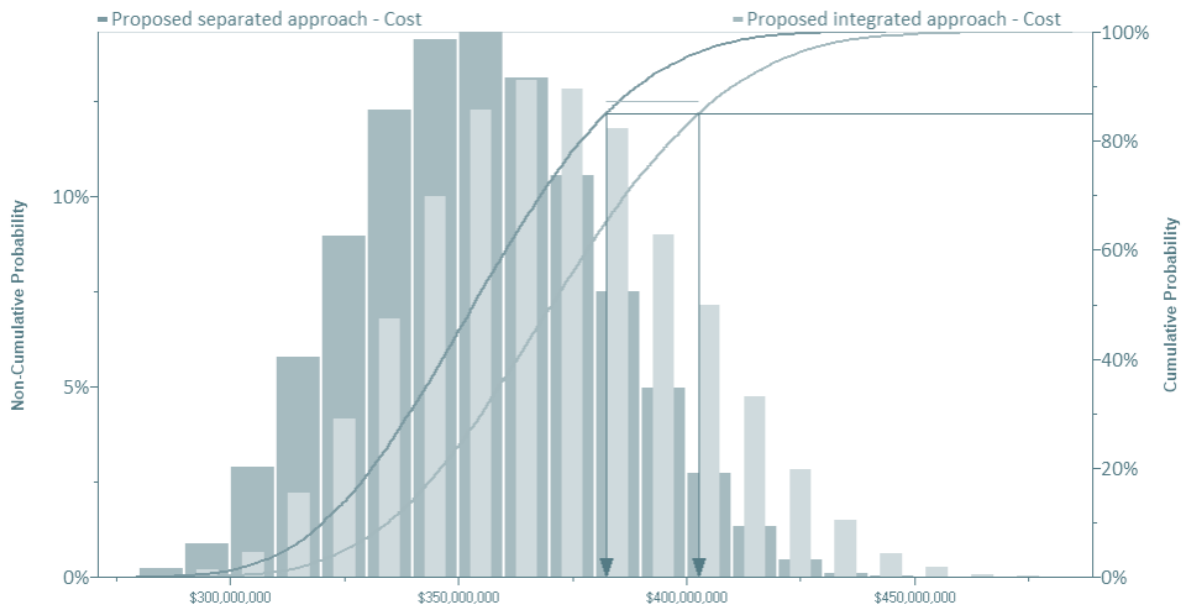


Figure 40: Cost distributions (P'CRA and P'ICSRA)

In Table 23 the cost contingency values estimated from each analysis are put against the actual consumed contingency.

Table 23: Cost contingency comparison (all analyses)

Analysis	Cost contingency required for P85	Difference from consumed contingency (58€ million)
C'CRA-1	2.63€ million	55.37€ million
C'CRA-2	22€ million	36€ million
P'CRA	35€ million	23€ million
P'ICSRA	55€ million	3€ million

There is a pattern of an increasing cost contingency estimate as more uncertainties are added in the analysis. Remarkably, the cost contingency derived from the C'CRA-1 is only 2.63€ million compared to the 58€ million consumed during the project. Of course, this analysis includes only risk events and it would make sense to be accumulated with the contingency derived from the C'CRA-2. It was not however, because the C'CRA-1 was conducted after the initial estimates were handed to the client. The cost contingency estimate from the C'CRA-2 ended up 36€ million short of what was actually consumed in the project. The cost contingency estimate derived from the P'CRA reduces this difference by further 13 million, but still falls short. Lastly, the cost contingency derived from P'ICSRA is much more accurate. It only lags the actual contingency consumption by 3€ million.

The graph in Figure 41 visualizes the consumption of the estimated contingency during the project for three scenarios. In each scenario a different initial cost contingency is assumed, taken from the three analyses (excluding the C'CRA-1).

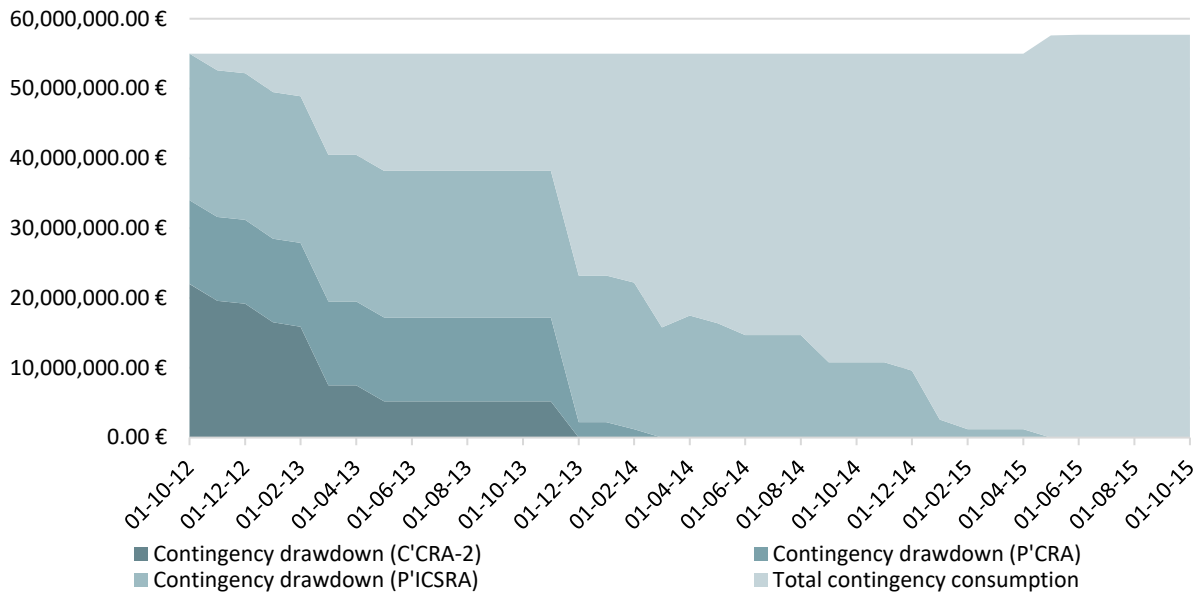


Figure 41: Contingency drawdown curves throughout the project for alternative scenarios

As it can be seen, the cost contingency from the C'CRA-2 is consumed rapidly and disproportionately to the project progress. Likewise, the contingency from the P'CRA is exhausted before the project midpoint. It is an incremental improvement over the C'CRA-2 though. The cost contingency from the P'ICSRA however, lasts almost until the project completion and provides a much better approximation of the reality. In the first two scenarios significant additional budget would be requested to compensate for the increased demand for contingency. This amount would be much lower if the P'IA was followed and the P'ICSRA was implemented.

In Table 24 the two cost risk events rankings, from the P'CRA and the P'ICSRA, are put next to each other. The two rankings are completely different. Notably, in the top-eight from the P'ICSRA, all but one risk events are schedule events. That means they were taken from the C'SRA and were not included in the C'CRA-1. Misleadingly, their impacts were mostly seen as schedule related. However, in the P'ICSRA schedule impacts influence the TD cost elements as well. Subsequently, the full extent of schedule risk events' impact on the cost side is revealed. As it turns out, the schedule risk events have greater contribution to the cost uncertainty than cost risk events.

Table 24: Cost risk events ranking comparison (P'CRA and P'ICSRA)

Separated cost analysis	Integrated analysis
Cost risk event 11	Schedule risk event 10
Cost risk event 16	Schedule risk event 1
Cost risk event 1	Schedule risk event 12
Cost risk event 12	Schedule risk event 7
Cost risk event 8	Schedule risk event 4
Cost risk event 14	Schedule risk event 2
Cost risk event 7	Cost risk event 11
Cost risk event 5	Schedule risk event 5

5.2 SCHEDULE OUTCOMES ANALYSIS

Key statistics, regarding the schedule outcomes from the analyses, are compiled in Table 25 and the generated distributions are shown in Figure 42.

Table 25: Key statistics for schedule (all analyses)

Analysis	Mean finish date	Finish date estimate at P85	Duration standard deviation	Probability of not exceeding the deterministic estimate
C'SRA	16/01/2015	09/02/2015	23 days	2%
P'SRA	11/02/2015	16/03/2015	29 days	<1%
P'ICSRA	11/02/2015	16/03/2015	29 days	<1%

The step from the C'SRA to the P'SRA saw an increase to both the mean value and the standard deviation of the distributions. The increase in mean value is mostly a result of the introduction of inherent variabilities with skewed distributions, while the increase in standard deviation is a combined effect of the introduction of inherent variabilities and correlation. It must be reminded that the schedule model used in the P'SRA and P'ICSRA, was much more detailed than the schedule model used in the C'SRA. As explained in Appendix 1, the more detailed the schedule, the more prone to suffer from the central limit theorem phenomenon, and thus to have an artificially small standard deviation. This is compensated by increasing the correlation coefficient in the model. Therefore, the produced standard deviation would be even higher if the same model was used in the P'SRA; but then a lower correlation should have been selected as well. The step from the P'SRA to the P'ICSRA, as expected, did not bring any changes to the schedule results.

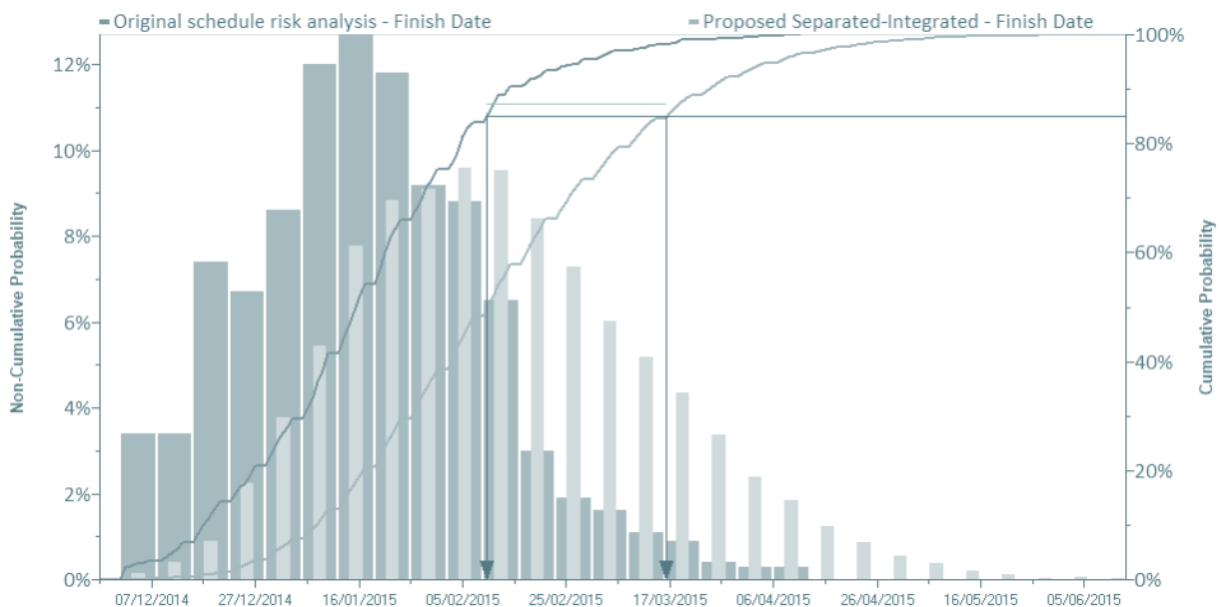


Figure 42: Finish date distributions (C'SRA and P'SRA)

The portion of the duration extension during the project that belonged to the contingency category could not be distinguished from the portion that was caused from scope changes, because of less meticulous record of time related data. This necessitated the assumption that schedule developments are proportional to cost developments which brings some limitations. Nevertheless, a comparison on this basis is performed and Table 26 gathers the required information.

Table 26: Schedule contingency comparison (all analyses)

Analysis	Finish date estimate at P85	Contingency required for P85	Difference from consumed contingency (60 days)
C'SRA	09/02/2015	70 days	10 days
P'SRA	16/03/2015	105 days	45 days
P'ICSRA	16/03/2015	105 days	45 days

The deterministic finish date was calculated to 1/12/2014 whereas the project completed on 31/10/2015, a 334 days difference. Out of that difference, 60 days were consumed as contingency according to the rule of thumb. The finish date output for an 85% confidence level from the C'SRA is 09/02/2015 which means 70 days of contingency added to the deterministic date. This value is 10 days over the actual contingency consumption. The P'SRA produces the finish date 16/03/2015 which means 105 days of added schedule contingency. This is 45 days over the actual contingency consumption. As expected the schedule results of the P'ICSRA are identical to the P'SRA. The results suggest that the C'SRA is better than the P'SRA and the P'ICSRA, because its schedule contingency estimate is closer to the actual schedule contingency consumption.

6 DISCUSSION

In this chapter a discussion is made about notable observations stemming from the research. In an effort to form a complete and all-around understanding, different viewpoints are taken to observe the situation from different perspectives. Implications concerning the following topics are discussed: contract type, contractor's and client's points of view, cost estimates and actual cost difference, level of effort, organization processes.

As observed in the case study project, the final cost of the project exceeded almost twofold the initial cost estimate. However, the organization still managed to make profits at the same level as originally projected. This is directly related to the fact that the contract was of reimbursable type and therefore most of the risk was taken away from the contractor. This does not mean that correct estimate of costs from the contractor's part is unnecessary when the contract type is reimbursable. Although at a lesser extent, risks are still present for the contractor, and in any case, it is very important for a contractor to make good impression to the client, to be favored for future projects. Inaccurate estimates that take the client by surprise are undesirable in that respect.

Also, because of the delay of the project and the cost overrun, the profit per work hour is reduced compared to the initial estimate. For an organization this measure is very important because it always strives to allocate resources in the most profitable way. It is more desirable to take on a short project with a certain amount of profits, than a longer project for the same amount of profits. Therefore, to select the most profitable project, correct cost and time estimates are important.

In case the contract is lump sum, the ramifications of not correctly estimating the costs are even more severe. In such a case the talking point would not be about maximizing profits, but whether losses will be avoided. A lump sum contract transfers most of the risk to the contractor's side. A wrong initial estimation can easily lead to diminishing profits or even incur losses. Correct and accurate estimation of cost in this case is of outmost importance and as observed the integrated approach is better in that respect.

However, as observed, the cost estimate deviated considerably from the actual overall cost (300€ million). The P'IA more accurate estimate of cost contingency, barely made a small contribution to reduce this difference. In case the project was lump sum, some of the change orders might not have been approved by the client and then the contractor could potentially sustain significant losses whatever the analysis performed for cost estimation.

At this point it should be noted that in a lump sum contract scenario, the company would proceed with a much more inclusive and rigorous risk analysis procedure. In principle, an organization is only concerned about the risks that might affect its profitability. This applies for the case study project. The company only dealt with the risks that could potentially impact its profitability. In a reimbursable contract type these are quite limited. Therefore, many of the potential risks that could have been identified and inserted in the company's analyses, were completely disregarded. This might be called an opportunistic behavior by the contractor, but then, the market laws dictate this kind of behavior. Including all the risks and subsequently calculating a higher cost estimate would have compromised the company's offer and the chances of winning the tender.

From the client's perspective the considerations are similar to what is described above from the contractor's point of view, but they apply to the opposite contract types. It is most important to a client to make an accurate cost prediction when the contract type is reimbursable, because most risk is on

his side. It is also very important, although to a lesser extent, when the contract type is lump sum. Of course, a client will always take a more holistic view and assess the project on its lifecycle rather than only on the execution phase, as a contractor will do. In this case the initial investment might determine whether the project in its entirety is considered feasible and profitable.

Given that the contractor included only “his” risks to derive the estimate, it is the client’s responsibility to deal with the rest of the risks. It is hard to imagine that the 300€ million difference is solely a consequence of the client’s failure to identify his own risks. A more realistic explanation is that the project was poorly defined at the time of the estimates. This view is reinforced by the large number of change orders. Other possible contributors to the 300€ million difference are uncertainty types that are not investigated in this research. Unknown unknowns for example, are risks that are unknown by definition. This does not mean they are impossible to expect or that they are completely unknowable. Instead, they are quantifiable only by very subjective assessment and therefore allowances can still be made for contingency (NASA, 2015). As Chapman and Ward (2011) state:

“Risk events’ and the inherent variability that much common practice risk management focus on are often the least important uncertainties, while ambiguity and systemic uncertainty are usually key”

The absence of unknown unknowns and other types of uncertainties from this research may contributed partly to the big difference between the original estimate and the actual cost. It is not regarded as a limitation however, because it does not impact the comparison between the different approaches.

Finally, part of the 300€ million difference can be attributed to the problematic cooperation between the contractor and the client. There are two profound spikes on the cost forecast graph in Figure 36 and finish date forecast graph in Figure 38. These spikes represent points in time when the contractor reviewed and updated the estimates for time and cost, based on the progress of the project and newfound information. At these spikes, the cost estimate is revised upwards considerably, but the following months is lowered again only to rise again later, at levels higher than the spike. This strange progression was explained by the contractor as an effort from their part to provide the client with a new plan and more realistic estimates, including measures to mitigate recent developments. Reasonably for them the cost estimate was substantially higher. The client however refused to accept this reality and requested a lower cost estimate and an earlier finish date. According to the contractor the client’s failure to acknowledge the reality only added to the problems that the project was experiencing, and magnified the consequences on cost and time.

An interesting matter, not thoroughly discussed yet, is the level of effort required to follow each approach. Modifying the cost and schedule models so that the corresponding elements are sufficiently aligned for integration, was the hardest and most labor-intensive part, not only of the P’ICSRA, but of the whole research. It can be easily inferred that more resources will be occupied to perform the P’IA compared to a SA. Then the reasonable question arises: “is it worth the extra effort?”. In an environment where the processes are designed to support a certain workflow, any effort to follow a different path will find a lot of resistance and obstacles. This also happened in this research when trying to implement the P’IA.

Particularly, when a SA is applied, the estimating and planning teams follow their respective workflows individually. It makes sense that they choose the most convenient and productive way for them to develop their models and perform their analysis. There is no guarantee that the paths they follow will converge. As observed in this research, the estimating team structured the cost elements according to

the discipline layout, while the planning team followed the work packages structure. Obviously the two workflows deviated considerably, and this amplified the effort needed to integrate time and cost.

This suggests that the processes within an organization used to perform a SA variant, should change substantially to provide an environment that supports an IA variant. First, the cost estimating and planning teams should work closely together and at least set a common standard for developing their models. This standard will make the integration process a lot smoother. The model used in the P'IA is based on a resource loaded schedule illustrated by a Gantt chart. Cost estimators usually work with spreadsheets and are not particularly familiar with schedule diagrams. However, for the integration to be performed transparently and smoothly, they should develop an understanding of schedules. In such a supportive environment the effort required for an IA can even be less than the effort required for a SA. Notably less software solutions are required for the analysis and only one analysis provides both schedule and cost outcomes.

7 CONCLUSIONS, LIMITATIONS & RECOMMENDATIONS

This chapter concludes the thesis by providing an answer to the main research question. Next, limitations are listed followed by recommendations to practice and suggestions for further research. Finally, a reflection on the whole experience puts an end to the report.

The main research question is:

To what extent do the outcomes of the C'SA, P'SA and P'IA differ from each other and which approach is more accurate?

The current study aims to provide empirical evidence about the performance of different risk analysis approaches by comparing C'SA, P'SA, P'IA and the actual outcomes of a real project. The answer to the research question is given in the following two steps:

From the C'SA to the P'SA

The results indicate an improvement when moving from the C'SA to the P'SA regarding the cost outcomes. Specifically, the cost contingency value from the P'SA lacks the actual cost contingency consumed by 23€ million, while the cost contingency value from the C'SA lacks the actual contingency consumed by 36€ million. This is a 13€ million difference. When looking at the schedule outcomes the C'SA fairs better. The schedule contingency estimate from the C'SA was 10 days over the actual schedule contingency consumption, while for the P'SA it was 45 days over the actual contingency consumption. This is a difference of 35 days.

From the P'SA to the P'IA

The results indicate to an improvement when moving from the P'SA to the P'IA. Specifically, the cost contingency value from the P'IA lacks the actual cost contingency consumed by 3€ million, while the cost contingency value from the P'SA lacks the actual contingency consumed by 23€ million. This is an improvement of 20€ million. The P'IA correctly assessed the cost impacts of all risk events and therefore produced a more accurate cost risk event ranking, while the P'SA failed to correctly assess the risk events that seemingly had only schedule impact and therefore produced a less accurate cost risk event ranking. The schedule related outcomes from the P'IA and P'SA fared equally. The P'IA produced outcomes useful for the monitor, control and management of a project that were unattainable from the P'SA.

Leaving the strict boundaries of the research question, some other conclusions can be drawn. First, the presence of the different types of uncertainty elements in an analysis can alter the results of that analysis considerably. This depends heavily on the extent to which the uncertainty type is included in the analysis. For example, in the P'CRA the impact of risk events on the distribution was low, whereas the impact of inherent variability and correlation was substantial. Also, the different uncertainty types affect different properties of the distributions. Correlation has an impact on only the standard deviation, while risk events and inherent variability have an impact on both standard deviation and mean value. Nevertheless, all uncertainty elements considerably affected the results of at least one analysis. Also, as observed in the P'ICSRA, the integration of time and cost elements, and the subsequent replication of the impact of schedule uncertainties on the cost variable, has a considerable impact on the cost distribution.

The "limited" C'SA performed better than the "more complete" P'SA and P'IA when looking at the schedule contingency outcome. This shows that the inclusion of all the uncertainty types does not necessarily provide the most accurate outcome over a single project. Also, a project is affected by

numerous factors not included in the risk analyses and therefore risk analysis is only part of proper cost and time estimation. As shown by the project results, the lion's share of cost and time developments is attributed to scope changes (or other factors) that came through change orders.

Through the implementation of both, the P'SA and the P'IA, a measure of relative required effort for each approach is developed. The P'IA required some additional steps, which were very demanding, like the integration of schedule and cost elements. It can be said that under the circumstances the P'IA is far more resource intensive than the P'SA.

During the case study project, both the contractor and the client exhibited strategic behavior. To large extent risk management was dictated by strategies and politics. Therefore, risk analysis was not performed in a strictly objective manner but instead it was used as an instrument to promote own interests. This was observed initially by the contractor by omitting risks not considered his responsibility and later by the client by requesting artificially lower estimates that were not realistic. Under these circumstances, the choice of risk analysis procedure would not be of high importance. Strategic choices would overshadow any benefits or drawbacks of the different analyses.

7.1 LIMITATIONS

The main limitation of this research is that only one case study is examined. The initial intention was to include more case studies, but limited time and resources, as well as limited number of projects that complied to the selection criteria, restricted the number to just one. The smaller the sample size, the less representative the results for the entire population. Consequently, the outcomes and conclusions while methodically derived, cannot be easily generalized. Notably, the cost and schedule contingency estimating comparison is made by using an 85% confidence level from every analysis. If another confidence level was selected the results might have been different. What this means is that for a robust conclusion on the performance of each approach, a large sample of projects should be taken and the percentage of projects finishing within the estimated values from the different analyses should be measured. The analysis whose results better replicate this success percentage (not being exceeded) will be the one performing the best. For example, when an 85% confidence level is selected, the better performing analysis is the one whose results are not exceeded over the 85% of the projects (or closer to that value).

The values of TD and TI cost elements were not always clearly defined in the project data. To infer these values, in some cases several assumptions and approximations were necessary. This may have caused a slight deviation between the calculated, and the real ratio of TD to TI cost elements, which in turn influences the outcomes produced by the P'IA.

The actual schedule contingency consumed could not be derived from the project data. These dictated a compromise by assuming that cost development during the project is proportional to schedule development. This is not necessarily true and therefore the actual contingency consumption during the project might be different than the one adopted. This compromise weakens the schedule contingency comparison outcomes

Finally, this research does not touch upon uncertainty elements other than the three described.

7.2 RECOMMENDATIONS TO PRACTICE

The overall experience during this research, the conclusion as well as the notable remarks that are presented in the discussion section, enable the conception of a set of recommendations for practice. As observed in the case study, the results produced by the C'SA fared poorly compared to the P'SA and

the P'IA. Considering the relatively big process changes required in the organization to effectively implement the P'IA, in the short term the focus should lay on transitioning towards the P'SA. This is a relatively easy task and the software solutions used in the company provide the necessary capabilities.

The main points of attention are:

- Incorporate all the cost related uncertainty elements into a single CRA and all the schedule related uncertainty elements into a single SRA
- Improve the models underlying each analysis. Specifically, the schedule model should be developed in accordance with the good scheduling practices to produce reliable results (Griffith, 2006). (avoid use of constraints and include the whole project scope)

In the longer term, a transition to the P'IA is recommended. The transition to the P'IA is a big step and requires fundamental changes to the processes in the organization, and potentially to its structure as well. However, it has the potential to enhance the collaboration between risk, estimating and planning teams by integrating and streamlining their processes. Furthermore, big clients and public bodies increasingly demand ICSRA from the bidders. In that respect, adopting an IA can be regarded as a strategic move by the company to gain a competitive advantage over competitors.

A notable concern is the large amount of scope changes that occurred during the project and their consequences on the actual outcomes. While it is impossible to define a project 100% accurately at its initiation, the large number of scope changes indicates that a fundamental shift is necessary in the bidding process especially for lump sum type of contracts. A recommendation is then to meticulously define the project before bidding for lump sum contracts, and to also perform a scenario analysis to examine the case of extreme scope changes and its implications on the project outcomes, and to also develop a strategy to counteract.

7.3 SUGGESTIONS FOR FUTURE RESEARCH

Based on observations from this research and the apparent limitations, the following suggestions for further research are formulated.

A more extensive similar research should be performed on a significantly larger project sample so that the results can be confirmed (or refuted) and the conclusions can be generalized. In this research the P'SA and the P'IA were retrofitted to the case study project and then compared to the actual results. This does not need to be the case though. An alternative could be to examine two groups of projects. One for which a SA was applied and one for which an IA was applied. Then identify the average underestimation or overestimation for each group and compare the approaches. Given a very large sample of projects this comparison can be valid.

Another interesting topic for research is to determine what changes are necessary to the processes and the structure of an organization to transition from separated workflow to an integrated workflow. Understanding the needs to provide a supportive environment for an IA, where it can be performed efficiently and effectively, is a very practical matter and can reveal the "real" level of effort compared to a SA.

Last but not least, an investigation on the matter of scope changes is considered of high importance. In the case study project, scope changes completely derailed the project from its original status. To avoid such situations fundamental changes are required to the bidding process and thinking. Either the project should be defined much more meticulously before bidding or the potential of scope changes and consequently the cost of change orders should be considered during the risk analysis practice. A

methodology on how to deal or avoid scope changes will be vastly beneficial for the successful execution of project and for the organizations in general.

7.4 REFLECTION

The thesis journey that started 8 months ago, and is coming to an end, has been tough and challenging but at the same time constructive and rewarding.

Thanks to FLUOR and its people I got the opportunity to experience how it is like to participate in a high-professionalism work environment. FLUOR is a century old company, a leader in its field and this is reflected throughout the company with high maturity and pre-established procedures in every business function and very knowledgeable individuals. I had high expectations before joining but I was still overwhelmed afterwards. I took advantage of this great opportunity and tried to connect with many colleagues to acquaint myself with the company and to absorb the maximum out of my internship.

During my time at FLUOR I acquired valuable insights about the construction industry in general. I had the opportunity to compare theory to practice regarding risk management. A valuable lesson I got is that a risk analysis procedure proposed in a guideline or a standard does not directly apply to the real world. There are innumerable factors affecting decisions and actions and a guideline can only do so much. I experienced this firsthand in my thesis when trying to apply the procedures derived from literature to the actual project.

Many problems appeared during the process and the solutions had to be found on the spot. Incompatible file types, for example, was a major issue at the initial stages of my research that necessitated the switch to different software solutions. This took some time and extra effort from my part, but in the aftermath it was a positive setback as I got accustomed with two risk analysis software solutions. Another challenge was the collection of data for the analyses. As described in paragraph 1.5.1, the large amount of data, the diverse nature of data, and the long time since the case study project completion, made the collection of data very cumbersome. It was required to filter through gigabytes of data, using multiple software, to retrieve what was essential for the research. Even after retrieving the data, the process of integrating different information (time, cost, risks), was a very challenging. Schedule and cost estimates were produced independently by different teams in different departments and their alignment proved to be painstaking. Last, the project that was finally selected was from the process industry. Having a civil engineering background, I was not familiar with this project type. Even though the nature of the research did not require specialized process related expertise, the lack of any process engineering knowledge made it harder to go through the project documents and grasp the general idea.

Finally, with the benefit of hindsight it is possible to detect where there was room for improvement in conducting the research. Due to the more technical nature of my prior civil engineering studies, I was overly consumed with technical details. While it is important to be precise, from a certain point on the extra effort outweighs the benefits. This attention to detail proved to create more problems and overcomplicate the solutions. Simpler solutions to some problems would have saved time without compromising the research. Also, on some occasions where a problem occurred, and the progress of the research decreased or stopped, I struggled for too long on my own before finally sharing the problem and taking a second opinion. Consulting a colleague or a professor earlier would have been wiser.

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APPENDIX 1: PROBABILITY THEORY ESSENTIALS

In this section the probability theory concepts that are important to understanding the research methodology are presented.

DISTRIBUTION

A probability distribution is a mathematical function that may be used to describe random variables that are subject to variation. These random variables may be discrete or continuous.

Discrete are called the random variables that can take values on a finite outcome space. A typical example is the coin flip experiment. The outcome space is composed of only two values: heads or tails. The occurrence of a risk event is like the coin flip. There are only two possible outcomes, it either occurs or not.

The probability that a random variable (X) may take a value lower than or equal to a particular value (x) is described by the cumulative distribution function. For a discrete random variable this function is given by the following equation (Jonkman et al., 2015):

$$F_X(x) = P(X \leq x) = \sum_{x \in \{X \leq x\}} f_X(x)$$

The probability that a discrete random variable may take a specific value out of the outcome space is described by its probability density function. This function is denoted by the following equation (Jonkman et al., 2015):

$$f_X(x) = P(X = x)$$

In many situations the variables under investigation take values from a continuous space. For example, some random variables may have units of time, as with the activity durations or costs as with the cost elements. Time and cost can take values in a continuous space⁵.

Just like a discrete random variable, the probability that a continuous random variable may take a value lower than or equal to a particular value is described by its cumulative distribution function. The function is denoted by the following equation (Jonkman et al., 2015):

$$F_X(x) = P(X \leq x)$$

The probability density function for continuous random variables is obtained by differentiating the cumulative distribution function. It is given by the following equation (Jonkman et al., 2015):

$$f_X(x) = \frac{dF_X(x)}{dx}$$

The probability density function multiplied with an infinitesimal interval yields the probability that the stochastic variable will take on a value within the interval. Contrary to the discrete random variables, the probability that a continuous random variable may take a specific value is 0 as shown in the following equation (Jonkman et al., 2015):

$$P(X = x) = 0$$

⁵ The option exists of using a discrete outcome space for these random variables if needed.

Figure 43 shows sample graphs for cumulative and density distribution graphs for discrete and continuous random variables.

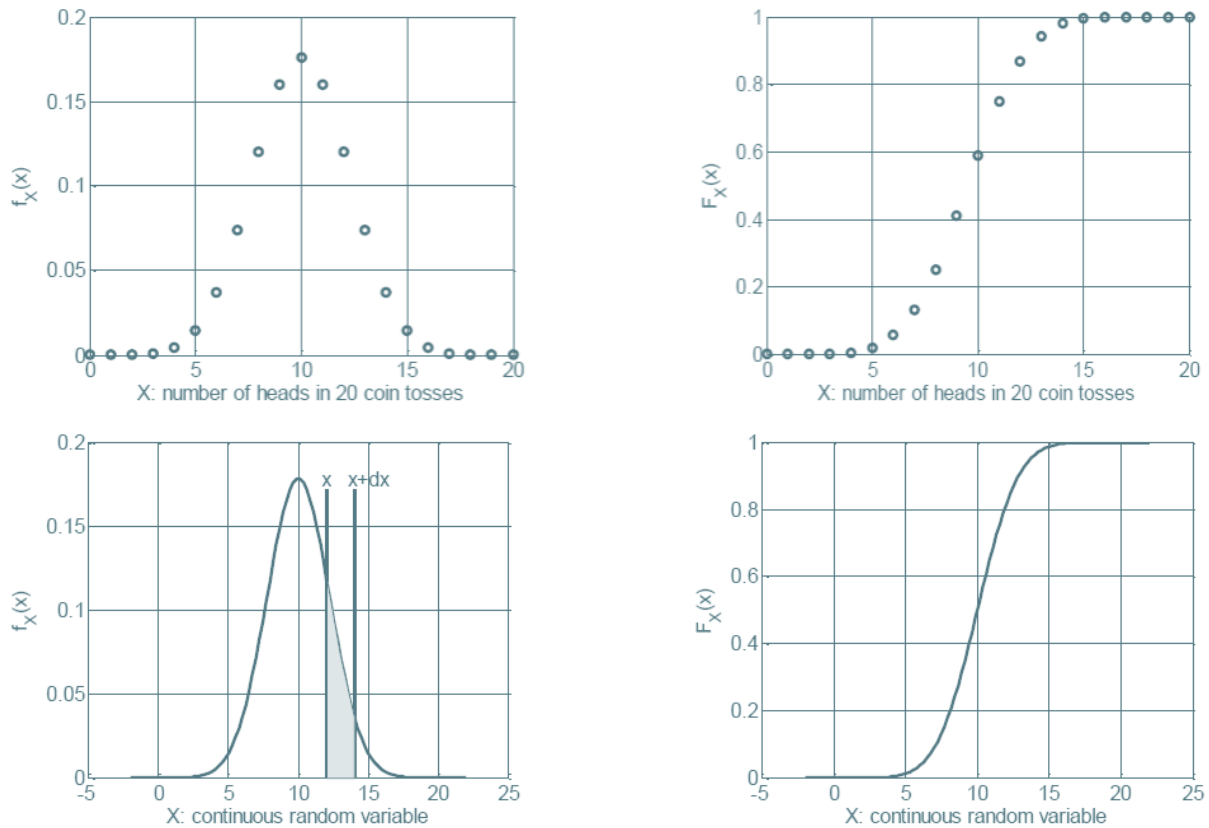


Figure 43: Distribution graphs for discrete and continuous random variables (Jonkman et al., 2015)

MEDIAN, MODE, MEAN

Mean, median, and mode are different measures that can be obtained from a distribution or a numerical data set. Often, they are mixed up and misunderstood. They represent different characteristic points from a distribution.

Figure 44, illustrates the meaning of each measure in a probability distribution. Median is the value separating the higher half of a distribution from its lower half. It indicates the point for which there is 50% probability of not being exceeded. Mean is the average value of the distribution. It is calculated by dividing the sum of values in a population by the number of values. Mode is the value appearing most often in a population. In a probability density function is the point where the distribution has a maximum value.

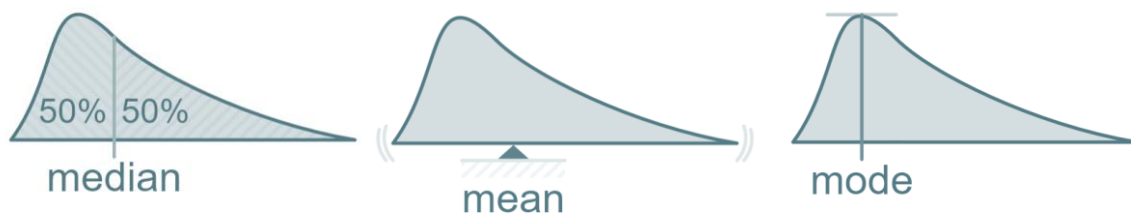


Figure 44: Median, mean and mode of a distribution

PARAMETRIC DISTRIBUTIONS

In many cases, a large enough sample from which a probability distribution can be formed does not exist. This is usually the situation when trying to describe the inherent variability of activities duration, of cost elements and of risk events impacts. In such cases inherent variability is replicated by using parametric distribution which can be completely characterized by a small set of parameters. The most commonly used distributions for these purposes are explained next.

UNIFORM DISTRIBUTION

The uniform distribution assigns equal density to all outcomes within an interval. In other words, all values within the range have equal chances to occur. Two parameters are required to define this distribution, a minimum value (a) and a maximum value (b). This distribution is often used as a “first guess” if no other information about a random variable is known, other than that it is in [a, b]. The density distribution function of a uniform random variable is described by the equation:

$$f_X(x) = \begin{cases} \frac{1}{b-a} & a \leq x < b \\ 0 & \text{otherwise} \end{cases}$$

The cumulative distribution function of a uniform random variable is described by the equation:

$$F_X(x) = \begin{cases} 0 & x \leq a \\ \frac{x-a}{b-a} & a < x < b \\ 1 & x \geq b \end{cases}$$

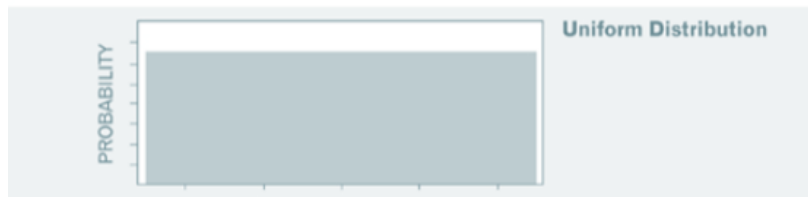


Figure 45: Uniform distribution

TRIANGLE DISTRIBUTION

The triangular (or triangle) distribution is one of the most commonly used distributions. Three parameters are required to define it, a minimum value, a mode value and a maximum value. These three parameters are usually associated with the optimistic, most likely and pessimistic estimates for a variable. This and the simple shape make this distribution easy to comprehend and therefore it is one of the most commonly used distributions. Triangular distributions are often skewed to the left when applied to task durations. This is because a lot of tasks cannot physically be completed in less than a certain duration, but all tasks can generally be delayed for a variety of reasons. This leads to the minimum duration being closer to the most likely than the maximum duration (Oracle Corporation, 2018) The same principle applies for cost elements. Usually a cost value can rise significantly but conversely cannot fall under a specific value. Its density function is denoted by the following equation:

$$f_X(x) = \begin{cases} \frac{2 \cdot (x-a)}{(c-a) \cdot (b-a)} & a \leq x < b \\ \frac{2 \cdot (c-x)}{(c-a) \cdot (c-b)} & b < x \leq c \\ 0 & \text{otherwise} \end{cases}$$

Its cumulative function is denoted by the following equation:

$$F_x(x) = \begin{cases} 0 & x < a \\ \frac{(x-a)^2}{(c-a) \cdot (c-b)} & a \leq x \leq b \\ 1 - \frac{(c-x)^2}{(c-a) \cdot (c-b)} & b < x \leq c \\ 1 & x > c \end{cases}$$

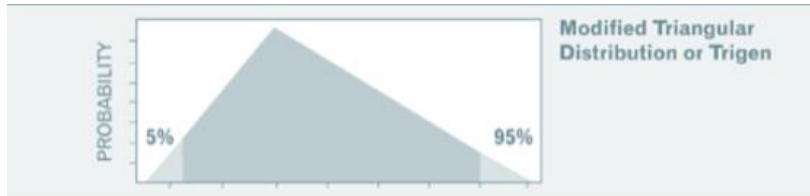


Figure 46: Triangular distribution

TRIGEN DISTRIBUTION

The trigen distribution has the same function as the triangular distribution. However, the development of the distribution differs slightly to provide a correction when the given minimum and maximum values are susceptible to bias. This is often the case during data collection, when individuals are asked to express their opinion on the ranges for certain variables. More often than not the ranges given are too narrow (Hulett & Avalon, 2017).

The trigen distribution requires 5 input parameters to be defined. Minimum (perceived), most likely and maximum (perceived) are identical to the triangular distribution parameter inputs. Additionally, two percentages parameters (limits) associated with the minimum and maximum values are required. These limits represent the probability that the perceived minimum and maximum values will not be exceeded. Then, the “true” minimum and maximum values are calculated by linear extrapolation (Oracle Corporation, 2018). Overall, by using the same three inputs from as with triangular, a wider distribution is generated to account for the potential bias.

BERNOULLI DISTRIBUTION

Bernoulli distribution is a discrete probability distribution. It describes a random variable that can take two possible outcomes, 1 or 0 (success or failure), in a single trial. It is a special case of the binomial distribution where many trials can be performed (Jonkman et al., 2015). In risk analysis it is used to simulate the existence or not of a risk event. It is defined by only one parameter, the probability of success., or of risk event occurrence in our case. Its density function is denoted by the following equation:

$$f_x(x) = \begin{cases} 1 - p & x = 0 \\ p & x = 1 \end{cases}$$

Its cumulative function is denoted by the following equation:

$$F_x(x) = \begin{cases} 0 & x < 0 \\ 1 - p & 0 \leq k < 1 \\ 1 & x \geq 1 \end{cases}$$



Figure 47: Bernoulli distribution

CORRELATION

In every analysis that involves random variables, it is important to know how the variables behave with respect to each other (covary). Correlation is a statistical concept directly related to the covariance and it measures the association between two variables (Jonkman et al., 2015). There are two prominent statistics for correlation. The Pearson correlation coefficient is the most common and measures the linearity of two variables, or equally, how well the relationship between two variables can be described by a linear function. The Spearman rank correlation coefficient measures the monotonicity of two variables, or equally, how well the relationship between two variables can be described by a monotonic function (R. P. Covert & Covarus, 2013). The two correlation statistics are different for different scatter plots as illustrated in Figure 48. When the scatter plot resembles an ellipsis and there are no outliers, like the middle plot, the Pearson and Spearman correlation coefficients produce similar values. Similar plots were generated from the software when a correlation coefficient for a pair of random variables was entered. Therefore, there was no need to specify what was the type of correlation in this research.

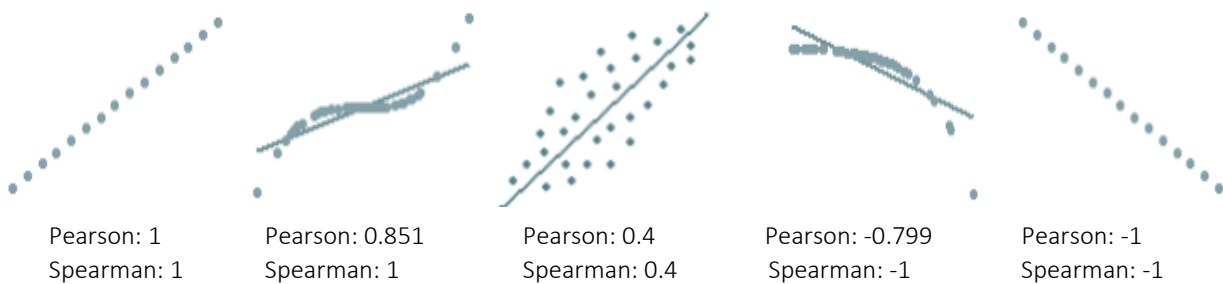


Figure 48: Pearson and Spearman correlation coefficient, adapted from Minitab Inc (2017)

SPECIAL CONSIDERATIONS FOR CORRELATION

The incorporation of correlation into the model and the analysis becomes increasingly important as the number of variables grows larger. This is caused by the statistical phenomenon of “Central Limit Theorem”. Because of this phenomenon the resulting distribution of an analysis has the tendency to approximate to a normal distribution and to be more tightly grouped around the mean value as the number of variables increases. As a result, if correlation is assumed zero, the underestimation at an 85% confidence level (for example) will be higher in models with a high number of variables. Figure 49 depicts this underestimation for different size models if the correlation was assumed to be zero.

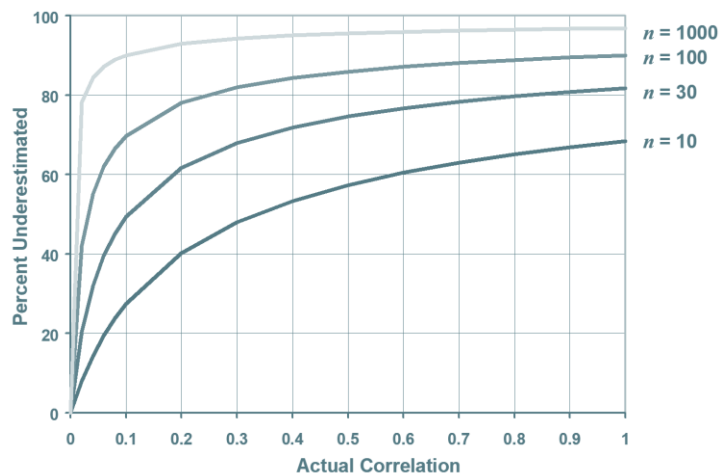


Figure 49: Underestimation of a cost value (R. Covert & Timothy, 2004)

In most software solutions that perform MC simulations, the assumption is made that all the elements to which distributions are assigned are uncorrelated to each other, and thus a value of zero is entered by default for correlation coefficients. Therefore, assigning correlation is a task that should be manually executed. The most common way of assigning correlation coefficients is through a correlation matrix. The matrix includes all the distributions for which a correlation coefficient can be given. The diagonal of the matrix is obviously filled with the value of plus one, as the distributions are perfectly correlated with themselves. The other matrix cells are filled with the correlation coefficient that is thought to be appropriate for the specific pair.

Importantly not all combinations of coefficients in the matrix are accepted. Depending on the inputs, an inconsistent or mathematically impossible matrix might occur. Usually software solutions have the capability to fix this issues by selectively adjusting pairs to make consistent matrix (Oracle Corporation, 2018). However, in the process the fixed matrix might change drastically from the one formed at the start and thus the new correlation status not representing the envisioned one. Another issue is that the number of pairs increases exponentially when the number of variables increases. In big or detailed models this makes for a very large matrix with thousands of pairs. Identifying and assigning a customized coefficient to every single pair becomes very cumbersome, even unfeasible. A common practice to overcome this peculiarity is to assign the same correlation coefficient throughout the matrix (apart the diagonal cells). This practice was also applied in the case study.

Another potential side effect of the large number of variables is the increase in processing load. The schedule model used in the case study has 1381 activities where inherent variability distributions are assigned. This makes for a 1381x1381 correlation matrix with a total of over 1,9 million cells to be assigned correlation. This huge number made the software to become slow and unstable. To overcome this, the correlations for task durations were applied in groups of activities that were considered most related to each other. In essence, this created multiple smaller matrixes which were much easier for the software to handle because the total number of pairs was lower. Specifically, after this modification, the number of pairs for which correlation coefficient was assigned reduced to around 0.5 million. The resulting effective correlation in this case is lower than the nominal one, entered in the cells, because many pairs are missing and thus considered to have a correlation coefficient of zero. However, this was offset by deliberately assigning a slightly higher nominal coefficient. The number of resources to be assigned correlation was small enough to not cause a similar problem and therefore no groups were formed.

If appropriate data is available, then correlation can be determined by performing residual analysis according to (R. Covert & Timothy, 2004). However, it is unlikely that either the required data are available, or the expertise to perform the statistical analysis is possessed. In cases of that no data is available, there is no acceptable standard for the value of the correlations coefficients to be used. According to Duncan et al. (2014) values of 0.25, 0.45 and 0.63 are suggested in literature, but a 0.3 is suggested by them. Hillson (2012), goes one step further and suggests that in the absence of better data, values of 0.7 or 0.8 should be selected.

Based on this information and adapting to the specific project the following values were selected. For the task durations a 0.5 correlation was selected and for the resource's variables a 0.4. The slightly higher coefficient for the task duration is to compensate for the large number of tasks and the "Central limit theorem phenomenon".

The risk factor method is another way of applying correlation to a model. This methodology works by assigning common factors/contributors of uncertainty. Each factor can affect several elements in the model. These elements are then functionally correlated with each other through the model and the

common underlying factors. The guesswork for correlation coefficients is removed in that way because the correlation is basically generated by the model and the multiple underlying factors. These factors can be the common contractor, or the steel prices as described before. While this method has some advantages, it necessitates the identification and quantification of the risk factors. In the project under investigation this was not performed by the organization and therefore the required data to proceed to this analysis were nonexistent. Also, the more traditional assignment of correlations through a matrix is a valid approach and one that is very common in practice. The risk factor is relatively new approach that would be an interesting subject for further research.

APPENDIX 2: UNCERTAINTY ELEMENTS PARTIAL INCLUSION (INTEGRATED MODEL)

In this section the contribution of each of the uncertainty elements on the cost and schedule distributions is examined in more detail. For that purpose, extra analyses were performed on the model used for the P'ICSRA, where different combinations of uncertainty elements are enabled. These partial analyses make it possible to measure the marginal contribution of each uncertainty element on cost and schedule outcomes. In the table the following abbreviations are used:

- Inherent variability: IV
- Risk events: RE
- Correlation: CO

IMPACT OF INHERENT VARIABILITY

The following table shows the marginal impact of inherent variability on project cost distribution. The presence of inherent variability of course creates a variance around a mean, analogous to the range width of the assigned distributions. If the distributions used for inherent variability were symmetrical, then the mean would be very close to the deterministic estimate. However, for the reasons already explained, the distributions used for inherent variability in this research are skewed to the right. Therefore, the mean of the resulting distribution increased compared to the deterministic estimate

Cost			Schedule			Min	Mean	Median	Max	σ	P85	P for deterministic	Contingency for P85
IV	RE	CO	IV	RE	CO								
---	---	---	---	---	---	337€ million	366€ million	366€ million	395€ million	8.2€ million	375€ million	1%	27€ million
+	---	---	+	---	---								

Similar effects are observed for schedule outcomes, as shown in the following table.

Cost			Schedule			Min	Mean	Median	Max	σ	P85	P for deterministic	Contingency for P85
IV	RE	CO	IV	RE	CO								
---	---	---	---	---	---	Deterministic estimate: 01/12/2014							
+	---	---	+	---	---	16/12/2014	24/01/2015	23/01/2015	23/03/2015	14 days	9/02/2015	<1%	70 days

IMPACT OF CORRELATION

The following table shows the marginal impact of correlation on project cost distribution. As already explained, correlation only exist between variables with distributions attached and therefore only when inherent variability is present. Correlation does not affect the mean value considerably. It increases however, the standard deviation of the resulting distribution and therefore the values at the extreme confidence levels.

Cost			Schedule			Min	Mean	Median	Max	σ	P85	P for deterministic	Contingency for P85
IV	RE	CO	IV	RE	CO								
---	---	---	---	---	---	Deterministic estimate: 348€ million							
+	---	---	+	---	---	337€ million	366€ million	366€ million	395€ million	8.2€ million	375€ million	1%	27€ million

+	-	+	+	-	+	280€ million	365€ million	365€ million	466€ million	27.8€ million	395€ million	28%	47€ million
---	---	---	---	---	---	-----------------	-----------------	-----------------	-----------------	------------------	-----------------	-----	-------------

The following table shows the marginal impact of correlation on project schedule. The low impact of correlation on schedule is mainly a consequence of the following modelling decision. As already described, because of computing power limitations, correlation coefficients were applied in groups of activities, to make the calculation process easier. This means that a lot of pairs of activities are not correlated. This also applies on the path that turns out as critical in a MC iteration. The fact that limited pairs of activities on that path are correlated, means that the effective correlation is lower than the nominal one assigned for each pair. This significantly decreases the effect of correlation on schedule. This is more of a limitation of the specific model under the given circumstances rather than a prove that correlation on schedule is unimportant. This limitation though does not negatively affect the research.

Cost		Schedule		Min	Mean	Median	Max	σ	P85	P for deterministic	Contingency for P85			
IV	RE	CO	IV									RE	CO	
-	-	-	-	-	-	-	Deterministic estimate: 01/12/2014							
+	-	-	+	-	-	-	16/12/2014	24/01/2015	23/01/2015	23/03/2015	14 days	9/02/2015	<1%	70 days
+	-	+	+	-	+	+	25/11/2014	19/01/2015	19/01/2015	08/04/2015	20 days	10/02/2015	<1%	71 days

IMPACT OF RISK EVENTS

Risk events can be distinguished in opportunities (positive impact) and threats (negative impact). Only one opportunity exists in the model. Therefore, as illustrated in the following table, risk events cause an increase of the mean value compared to the deterministic estimate. The fact that the impacts of risk events are subjected to inherent variability created the substantial standard deviation.

Cost		Schedule		Min	Mean	Median	Max	σ	P85	P for deterministic	Contingency for P85			
IV	RE	CO	IV									RE	CO	
-	-	-	-	-	-	-	Deterministic estimate: 348€ million							
-	+	-	-	+	-	-	349€ million	358€ million	357€ million	382€ million	6.1€ million	365€ million	<1%	17€ million

Similar results are observed for schedule, as shown in the following table.

Cost		Schedule		Min	Mean	Median	Max	σ	P85	P for deterministic	Contingency for P85			
IV	RE	CO	IV									RE	CO	
-	-	-	-	-	-	-	Deterministic estimate: 01/12/2014							
-	+	-	-	+	-	-	01/12/2014	30/12/2014	25/12/2014	08/04/2015	24 days	27/01/2015	15%	57 days

IMPACT OF SCHEDULE UNCERTAINTIES ON COST

As already described in paragraph 5.1 and shown in Table 22, schedule uncertainties have a significant impact on the cost results. The following table completes the data shown in Table 22.

Cost		Schedule			Min	Mean	Median	Max	σ	P85	P for deterministic	Contingency for P85
IV	RE CO	IV	RE	CO								
Deterministic estimate: 348€ million												
+	+	+	-	-	277€ million	355€ million	355€ million	446€ million	26€ million	383€ million	40%	35€ million
-	-	-	+	+	347€ million	366€ million	365€ million	402€ million	7.8€ million	374€ million	<1%	26€ million
+	+	+	+	+	288€ million	372€ million	371€ million	484€ million	29€ million	403€ million	22%	55€ million

Schedule is not affected by cost related uncertainties as observed in the following table.

Cost		Schedule			Min	Mean	Median	Max	σ	P85	P for deterministic	Contingency for P85
IV	RE CO	IV	RE	CO								
Deterministic estimate: 01/12/2014												
+	+	+	-	-	>>	>>	>>	>>	>>	>>	>>	>>
-	-	-	+	+	26/11/2014	11/02/2015	10/02/2015	16/06/2015	29 days	16/03/2015	<1%	105 days
+	+	+	+	+	>>	>>	>>	>>	>>	>>	>>	>>

APPENDIX 3: INPUTS FOR THE ANALYSES (CONFIDENTIAL)