Thesis for the degree of Master of Science in Marine Technology
in the specialisation of Ship Production

Discovering the Potential of Risk-based Critical Chain Project Management in the Maritime Industry

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By

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Summary

There is a never-ending quest to search for better ways of planning and controlling projects. Currently the majority of all projects are planned with the critical path method and controlled using earned value management. This way of planning and controlling projects has been used for decades now and can be seen as traditional Project Management (PM). This current project management paradigm does not work well enough for one-off projects. Statistics show that 30% of the world's economic activities are arranged and performed in a project approach. Many of those projects fail to deliver in terms of on time, within budget and with the promised quality/scope.

It has been found that the causes of project failure can mostly be related to:

- Dealing with changes (events) during the project
- Inaccurate estimates of time and costs
- Management of risks and uncertainties
- Dealing with resources (dependencies, forecasting and limits)
- Procrastination

The solution of this research aims to improve PM on the five listed points. The alternative PM methodology Critical Chain Project Management (CCPM) is chosen as foundation. In general, risk assessment is not a part of the standard PM method, while it could solve much of the causes of project failures. Therefore, Monte Carlo simulation and event chain methodology are part of the solution, which changes CCPM into Risk-based Critical Chain Project Management (RCCPM).

The goal of this research is stated as: *To find a way to better plan and control projects with a specific focus on the project's risks and uncertainties in order to improve project performance.*

The main research question is: *Is Risk-based Critical Chain Project Management a viable alternative for traditional project management in the maritime industry?*

Answers to the research questions are provided by means of five different activities.

1. A literature review into CCPM.
2. A study into the experiences of other organisations with CCPM.
3. Developing the RCCPM method and tool.
4. Applying the developed RCCPM tool to a set of case studies and comparing this with the traditional approach, both for lead-time reduction and difference in progress reporting.
5. A survey on the RCCPM type of progress reporting compared to traditional progress reports.

The study concluded that RCCPM is a viable alternative for traditional PM in the maritime industry. RCCPM has shown significant improvements relative to traditional PM:

- A reduction of the lead-time
- More effective in monitoring and controlling
- Improved dealing with risks and uncertainties

RCCPM can be applied in the maritime industry and the case studies are an example of this. No barriers have been found to introduce RCCPM on a day-to-day basis in organisations and projects similar to the ones investigated in this research. The RCCPM tool has used well-known, well-tested software, chosen after extensive comparisons of the available software, which makes it easy for other organisations to use.

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List of Abbreviations

AC	Actual Cost
AHP	Analytical Hierarchy Process
BAC	Budget at Completion
CCPM	Critical Chain Project Management
CI	Criticality Index
CPI	Cost Performance Index
CRI	Cruciality Index
CV	Cost Variance
DVR	Damen Verolme Rotterdam
ECM	Event Chain Methodology
ETC	Estimate to Complete
EV	Earned Value
EVM	Earned Value Management
FB	Feeding Buffer
LCL	Lower Control Limit
MC	Monte Carlo
OWTF	Offshore Wind Turbine Foundation
P	Probability
PB	Project Buffer
PM	Project Management
PMBOK	Project Management Body of Knowledge
PMI	Project Management Institute
PV	Planned Value
RBCI	Relative Buffer Consumption Index
RCCPM	Risk-based Critical Chain Project Management
RSEM	Root Square Error Method (identical to SSQ)
SSQ	Square Root of the Sum of the Squares (identical to RSEM)
TOC	Theory of Constraints
UCL	Upper Control Limit
VOR	Variation Order Request
WIP	Work in Progress

1. Introduction

This chapter introduces the company in the first section and the problem statement of this research in the second section, followed by the undesired effects to be eliminated by CCPM (the solution direction) in section 3. Section 4 describes the objectives and research questions. The fifth section makes the scope clear, followed by a description of the methodology in section 1.6. The structure of this report is explained in section 1.7. A scientific paper is added to appendix 1.

1.1 Company Description: Damen Verolme Rotterdam

Damen Verolme Rotterdam (DVR) (former Keppel Verolme) is a ship and offshore yard, located in the port of Rotterdam, the Netherlands. The yard is founded by Cornelis Verolme in 1957 and was part of Keppel Offshore & Marine since 2002. On the 1st of July 2017 Keppel Verolme has been acquired by Damen Shiprepair and Conversion. The yard has three dry docks, the largest one being 90 x 405 m, and is therefore able to accommodate almost any ship or offshore unit. The company's main services are dry docking, repair and maintenance, modifications, conversions and constructions. Besides, the yard is currently actively pursuing orders in the offshore wind and decommissioning markets.

When it comes to PM, the corporate brochure says, "We have acquired extensive experience in planning, control and management of projects. We are experts in managing large numbers of man hours in relatively short periods of time. It is Keppel Verolme's obligation to organise the management of the projects in a clear and effective way to achieve the essential objectives of the project." (Keppel Verolme, 2016).

1.2 Problem Statement

There is a never-ending quest to search for better ways of planning and controlling projects. Currently the majority of all projects are planned with the critical path method and controlled using earned value management (EVM). This way of planning and controlling projects has been used for decades now and can be seen as traditional Project Management (PM). This current project management paradigm does not work well enough for one-off projects. Critical path planning has not been modified significantly since its introduction in the 50's (Shou & Yeo, 2000). The Project Management Body of Knowledge (PMBOK), as developed by the PMI (Project Management Institute), is seen as the standard work for traditional PM in this research and is an ANSI (American National Standards Institute) norm (Project Management Institute, 2013).

Statistics show that 30% of the world's economic activities are arranged and performed in a project approach (Turner, 2009). Many projects fail to deliver in terms of on time, within budget and with the promised quality/scope. Research has been carried out by others, which can support and elaborate this proposition.

KPMG conducted a survey with 52 respondents, showing that only 8% can say that the majority of their projects (more than 75%) deliver on time, within budget and with 90% realised scope. About 31% of the respondents indicated that 50-75% of their projects achieved the above stated criteria. The rest, which is the majority, completed only less than half of their projects as planned (KPMG, 2015).

Another survey of KPMG in New Zealand from 2012 shows that only 33% of the respondents consistently delivered projects on budget, 29% on time and 35% delivering stated deliverables (KPMG, 2013).

There are a variety of reasons why so many projects fail. Again, some studies have been done, with the most recent one asking the question: "Of the projects started in your organisation in the past 12 months that were deemed failures, what were the primary causes of those failures? (Select up to 3)" (Project Management Institute, 2016). From the answers, a visualisation can be generated (Figure 1).

Figure 1: Causes of project failures, data from (Project Management Institute, 2016)

The numbers show that there is quite some room for improvement. This improvement can be accomplished in two vastly different kinds of approaches.

1. Incrementally improving the current traditional way of PM
2. Radical improvement by introducing another method of PM

This research focuses on radical improvement, as this is the approach to get substantial improvements. It is however more difficult and time consuming to implement into an organisation. This has to be known, but change management will be out of scope for this research. The need for an alternative method is strengthened by the fact that critical path planning often fails and that even expensive software cannot improve this (Rand, 2000).

The question is then where to focus on with improving PM by using another method, as there are multiple alternative methodologies available. A lot of causes of project failures from Figure 1 can be related to:

- Dealing with changes (events) during the project (1, 2 & 9)
- Inaccurate estimates of time and costs (6 & 10)
- Management of risks and uncertainties (4 & 16)
- Dealing with resources (dependencies, forecasting and limits) (11, 12 & 13)
- Procrastination (15)

Please keep these five listed causes of project failure in mind, as these will be frequently referred to in later parts of this report.

Also at Damen Verolme Rotterdam, there is an increasing demand from customers to have a robust project plan with the certainty of having no schedule delays and/or cost overruns. The solution of this research aims to improve PM on the five listed points. One of the available alternative methodologies that promise to have the potential to do that is called Critical Chain Project Management (CCPM). The undesired effects to be eliminated by CCPM are described in the next section.

In general, risk assessment is not a part of the standard PM method, while it could solve much of the causes of project failures. Therefore, Monte Carlo simulation and event chain methodology will be a part of the solution. Section 3.3 will elaborate on these techniques, which change CCPM into Risk-based Critical Chain Project Management (RCCPM).

1.3 Undesired Effects to be eliminated by CCPM

CCPM aims to eliminate six undesired effects which are commonly observed in traditional PM and which can also be found at DVR, those six are (Leach, 1999):

1. Little actual activity positive variation
2. Failure to pass on positive variation
3. Project delay caused by activity path merging
4. Multitasking
5. Loss of focus
6. Excessive activity duration estimates

Each one of them will be explained in the subsections below.

1.3.1 Little Actual Activity Positive Variation

Nowadays projects are often planned with task durations of about 90-95% probability of finishing on time. This should also mean that about 90-95% of the activities are delivered on time and many of them even before, this is however not the case. The distribution is not in balance, there is hardly any positive variation, but a lot of negative variation. There are several effects in human behaviour that can be related to this.

1.3.1.1 Student Syndrome

The student syndrome describes the phenomenon of postponing the starts of a task, because there are other tasks you like more or that have a higher priority. The task is not started until it is really needed; meaning that all the available contingency time is already used even before starting the activity. This already means days are lost, days that did not add any value to the task at hand. Rand (2000) puts forward that employees think that they do not need to worry about starting on time, because they know that contingency time is built into the estimates. Now if Murphy's Law strikes the project is directly delayed, even though there was so many contingency added to the planning. Figure 2 shows this typical work behaviour.

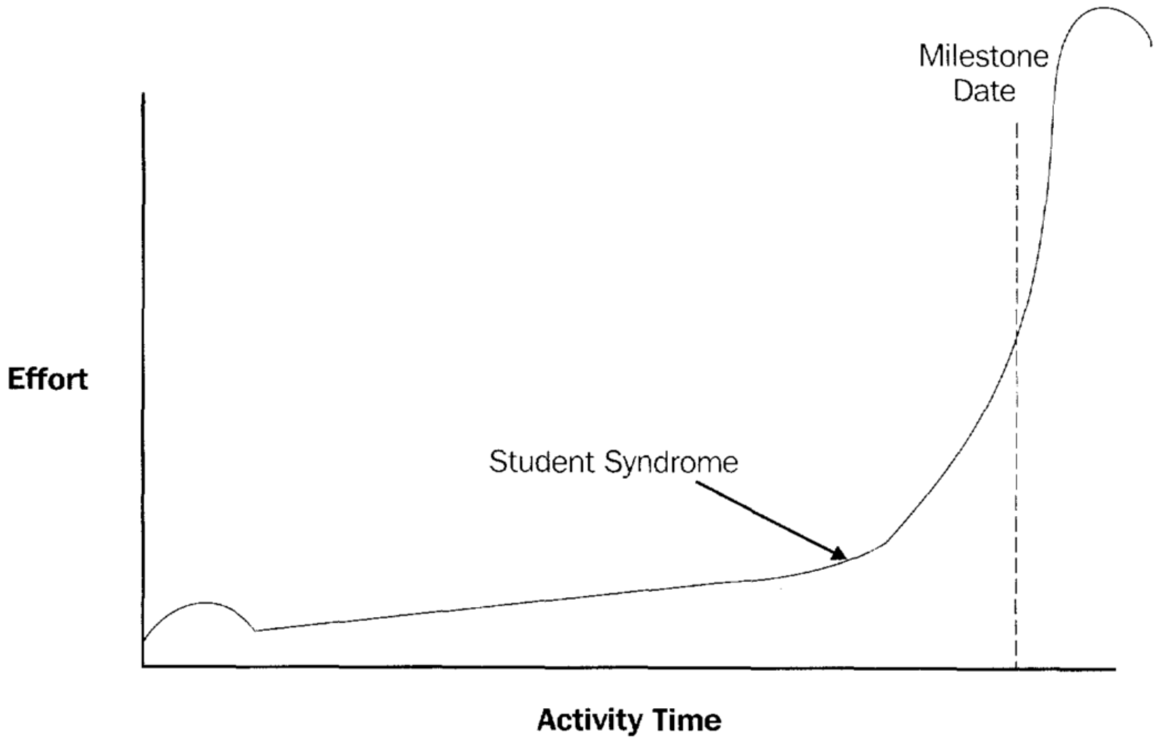

Figure 2: Typical work behaviour due to student syndrome (Leach, 1999)

1.3.1.2 Parkinson's Law

Contrary to the student syndrome, it is also possible that you really like to work on the task or that there is no other task to work on, so you start immediately. There is however no reward or incentive for being ready so early, but the risk of not delivering the work according to their manager's expectations is on their account. It is also possible that the department loses its right to charge on the project account. The extra time will thus be used to add some extra things to the task at hand and to relax a bit before starting a new activity. This behaviour is known as Parkinson's Law (Figure 3) and is formally written down as "work expands so as to fill the time available for its completion" (Gutierrez & Kouvelis, 1991; Parkinson, 1955). Other authors refer to this behaviour as "gold plating" (Steyn, 2001). Again, contingency time is wasted.

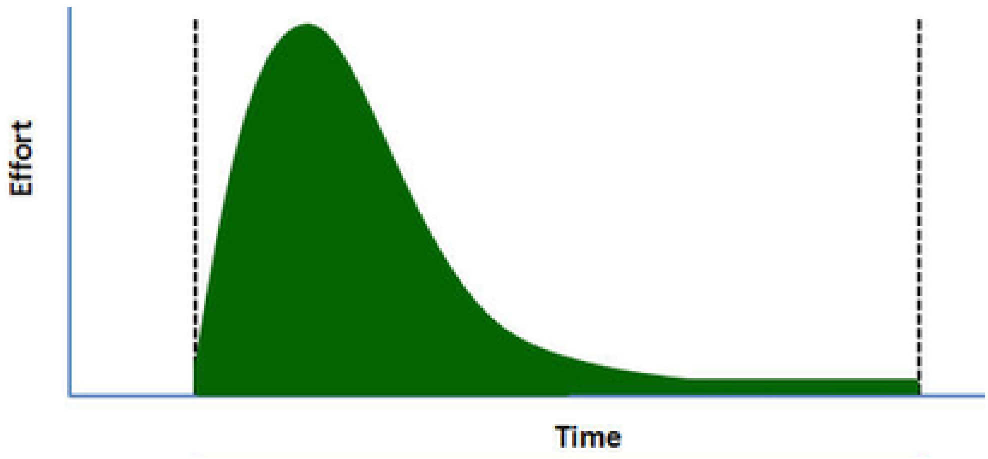

Figure 3: Typical work behaviour due to Parkinson's Law

1.3.2 Failure to Pass on Positive Variation

Steyn (2001) describes that in traditional PM "any delay of a critical activity would delay the project, but the opportunity of one that is accelerated would generally not be seized". There is (almost) no reward for finishing a task early in most cultures (Leach, 1999; Steyn, 2001). You lose budget or have to do more, so there is no incentive to deliver before due date. Contingency time will thus be used anyway, if it is really needed or not. An experiment of milestone performance on a large project with over 15000 activities gives a numerical justification to Goldratt's proposition that about 80% of the activities are delivered exactly on the scheduled date (Leach, 1999). It seems clear that a large amount of those 80% could have been delivered before the scheduled date. Figure 4 illustrates this undesired effect.

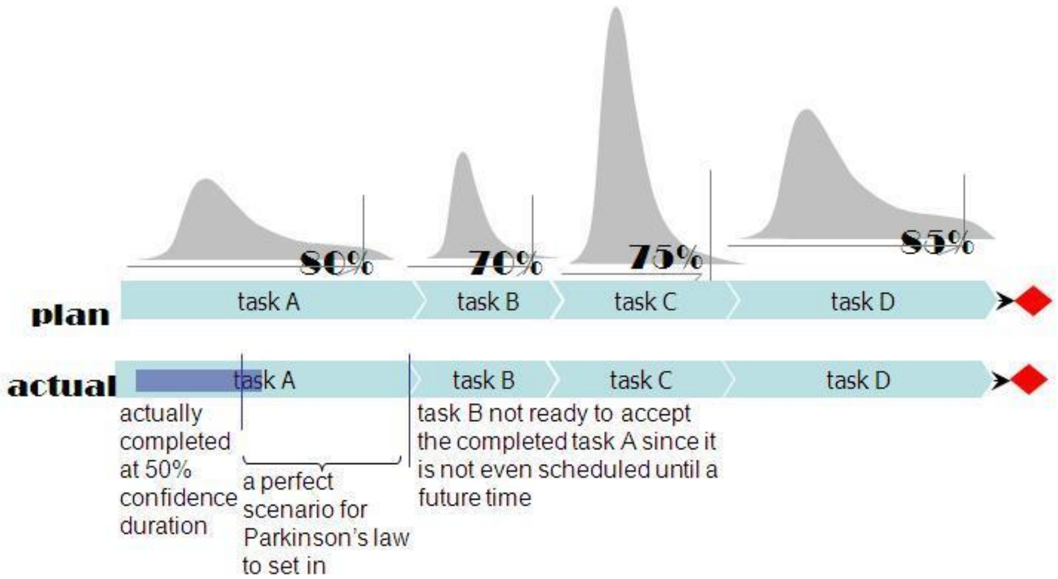

Figure 4: Failure to pass on positive variation (Planstrat Inc., 2009)

1.3.3 Project Delay Caused by Activity Path Merging

Most projects have multiple paths of activities that usually come together at the end of the project. This merging of activity paths eliminates any positive variations as it passes on the longest duration (see Figure 5). The PMBOK Guide acknowledges this effect by stating that “schedule simulation should be used on any large or complex project since traditional mathematical analysis techniques such as the critical path method do not account for path convergence and thus tend to underestimate project durations” (Project Management Institute, 2013).

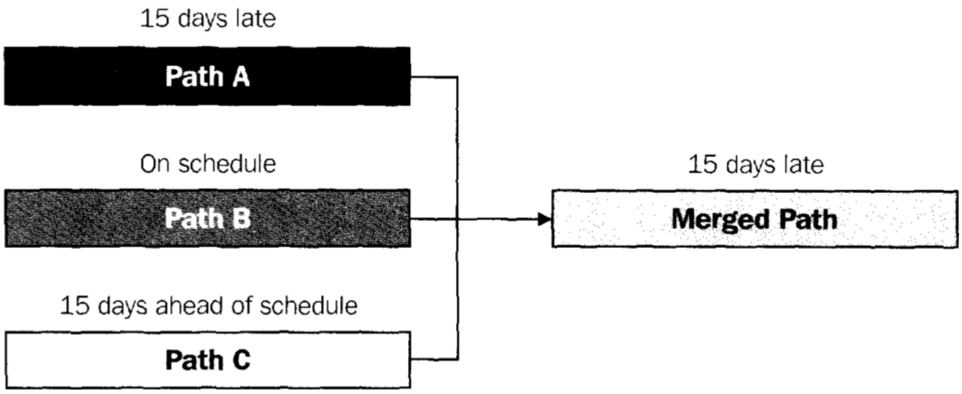

Figure 5: Effect of activity path merging (Leach, 1999)

1.3.4 Multitasking

It is often seen in multi-project environments that engineers are assigned to multiple projects at the same time. Suppose an engineer gets three tasks, which he thinks take three days each. Ideally, he would first work on task A until completion, then task B until completion and end with task C. This should take him nine days. In reality it is often seen that all three tasks are worked on alternately, leading to a longer total duration. CCPM provides clear priority rules to stick to in order to eliminate multitasking. This reduces work in progress (WIP) and increases focus, which is one of the main points of CCPM. Therefore, tasks are planned to start as late as possible which is counterintuitive to the traditional paradigm of starting as early as possible.

Goldratt (1997) describes multitasking as “the biggest killer of lead time”. Leach (2014) argues, “Perhaps the largest project execution problem is that most organisations allow or even encourage people to multitask on a daily or weekly basis”. He stresses that focusing on one task at a time can greatly improve project performance and sees multitasking as a root cause of project failure (see Figure 6). CCPM is presented as a solution for this.

Leach (2014) describes in his book an experience of the benefits of eliminating multitasking for the repair of nuclear submarines at the Pearl Harbour Naval Shipyard in Hawaii. Before CCPM, projects were often not finished on time and crews were frequently reassigned during the project. CCPM ensured a focus on better preparation, so the chance of crews changing projects was decreased. The results of this example clearly show the potential of CCPM: “nearly all submarines left on time with much more work done at less cost than happened previously”. Moreover, quality defects went down by 50%, productivity increased by 100% and costs decreased due to less overtime.

Medina (2008) argues, “The brain cannot multitask”. Our brain is only able to pay attention to one task at a time. Studies have shown that it takes 50% longer to finish a task if someone is interrupted.

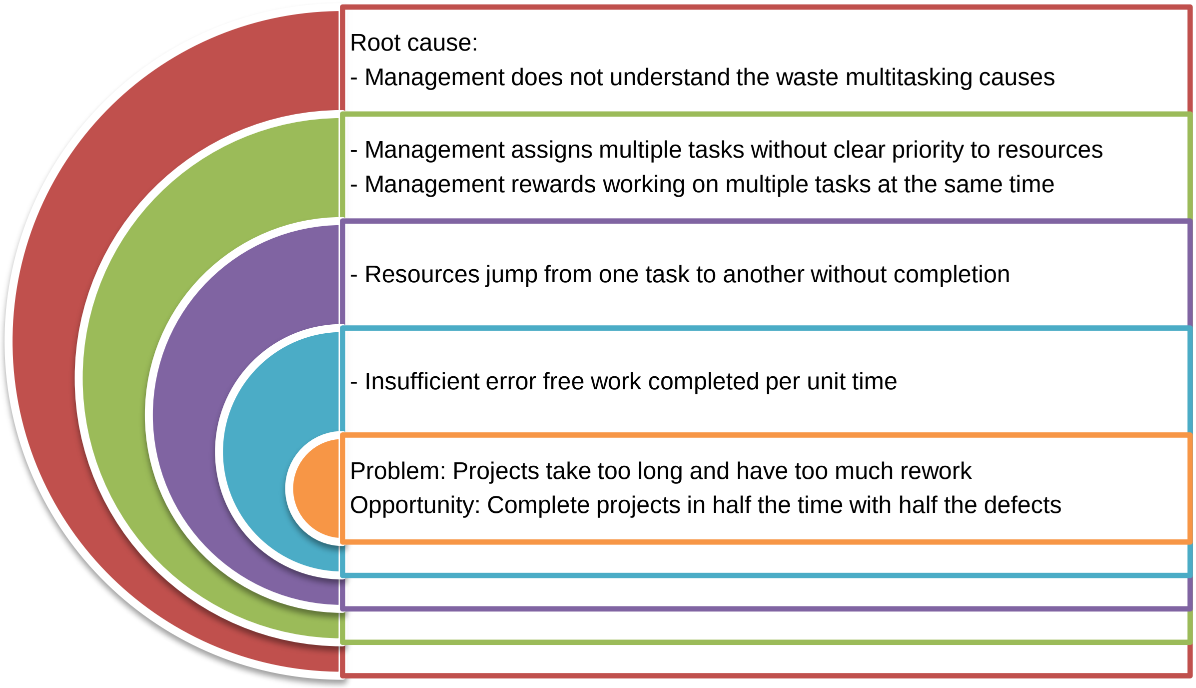

Figure 6: Multitasking as a root cause of project failure (adapted from Leach, 2014)

Rubinstein, Meyer & Evans (2001) identified two stages in the executive control of cognitive processes in task switching; goal shifting and rule-activation. It appears that constant changing of the rules causes stress.

A study from Stanford showed that people who often perform multitasking "are more susceptible to interference from irrelevant environmental stimuli and from irrelevant representations in memory" (Ophir, Nass, & Wagner, 2009). This resulted in the fact that people who often multitask performed worse on a task-switching test than those that do not.

Leach (2014) considers the following research-proven effects of multitasking:

- Everything takes longer
- Effects in organisation are worsened
- Stress levels increase
- You get less done
- Time is wasted with each switch of attention
- Learning is reduced
- More mistakes are made

1.3.5 Loss of Focus

According to Leach (1999) there are several aspects in current PM that make it hard for the project manager to know where to focus on:

- Activities are traditionally planned to start as early as possible, meaning that many activities start directly at the start of the project. This makes it difficult for the project manager to have the right attention.
- The critical path often changes during project execution, meaning the attention shifts all the time.

- The use of only earned value (EV) to control a project. EV does not discriminate between activities on the critical path and those who are not. It also does not indicate the effect of other paths on the critical path.
- Too often and too soon using the EV thresholds resulting in many control actions. This behaviour is identified by Deming (1986) as tampering; trying to decrease variation that is still in the range of common cause variation.

1.3.6 Excessive Activity Duration Estimates

Most projects are planned with contingency time included in every activity duration estimate to deal with individual common cause variation. The exact level of probability is in reality often not known, but usually low-risk estimates are made with about 90-95% of probability to complete on or before the specified date. Figure 9 shows that a low-risk estimate could be 2-2.5 times as much as the 50% probable estimate. Leach (1999) argues that in many projects “people feel good if they complete an activity by the due date, and feel bad if they overrun the due date. This reinforces their attempts to estimate high probability completion times”.

It is also common practice in a lot of organisations that “managers at each level of the organisational hierarchy tend to add their own precautionary measures on top of the estimates of managers or co-ordinators reporting to them” (Steyn, 2001). Imagine for instance an organisation with four layers where each person adds 20% extra contingency time, this would lead to a total duration of 1.2^4, which is more than double of the original estimate. According to Steyn (2001) the most important point of CCPM is not its problem with the amount of contingency in the planning, but the wrong location: it should be placed at a project level instead of at each activity.

High contingency levels in an organisation can lead to too long tasks at the end of a planning. Many organisations work according to the principle of adding contingency at multiple layers. A simple example to demonstrate how this principle works in many organisations is visualised in Figure 7. For simplicity reasons the focus is on two engineering tasks, executed by two different engineers. Both engineer 1 and engineer 2 are asked to give an estimation of the work. They think it should be possible in three days, but tell their team leader “I can do it in one week”. At this point, there is already four days of (hidden) contingency in the planning. The team leader hears both tasks take one week and he knows that engineer 2 cannot start his task before engineer 1 finishes his task. Therefore, he decides to tell the project manager “The engineering part should be planned for 12 days”. The project manager however has some concerns, because there are some large tasks to be finished before the engineering. Therefore, he decides to plan three weeks for the engineering. See how fast this process goes, from six to fifteen days. This may seem to be an extreme case, but it is actually reality in many organisations. Even if the layered planning structure does not apply to the organisation, there is still contingency to be cut from the planning.

CCPM is, at least in theory, able to reduce these large amounts of contingency in the planning. An optimal implementation of CCPM should get rid of the multiple layered planning structures and excessive contingency times that will be filled for numerous reasons. Instead, the engineers initial three days estimation has to be known and in order to reduce the risk of not finishing on time a buffer has to be made and managed. Now many people might say, “It doesn’t matter how many days the engineer gets for the task, if he can do it in three days, he will do it in three days". There are some aspects of human behaviour why this is very often not the case; these have been explained in the previous subsections.

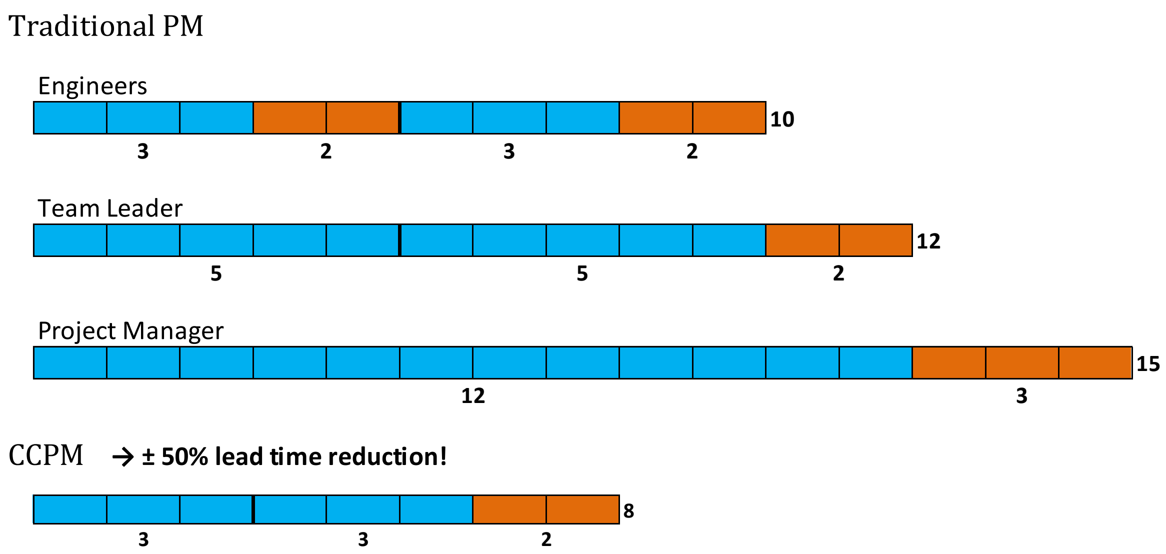

Figure 7: Demonstration of contingency in a planning

1.4 Objectives and Research Questions

The ultimate goal of this research is:

To find a way to better plan and control projects with a specific focus on the project's risks and uncertainties in order to improve project performance.

The main research question is:

Is Risk-based Critical Chain Project Management a viable alternative for traditional project management in the maritime industry?

RCCPM would prove to be viable in case project performance improves in comparison to traditional PM, not only in theory but also in reality. Project performance entails an on time, on budget and according to scope delivery. This would be the case if RCCPM can reduce the five listed causes of project failure. Another part of viable is the fact if an organisation can actually work according to the principles of RCCPM and if RCCPM can be applied to the maritime industry.

Sub research questions are defined to make this main research question more specific and to aid in finding an answer to the main research question.

1. Is the developed RCCPM tool able to effectively compare the results from RCCPM and traditional PM?
2. Is RCCPM better able to take risks and uncertainties into account than traditional PM?
3. Is RCCPM more effective in monitoring and controlling projects than traditional PM?
4. Does RCCPM lead to earlier completion of projects in comparison with traditional PM?
5. Is there a difference in the application of RCCPM for complex specials and serial production? If yes, what is the difference?
6. What are the requirements for an organisation to adapt its PM method to RCCPM?

The first sub question is needed to enable the use of the tool to provide answers to the other five sub questions. If the tool is not able to make a good comparison or to make a good estimation of the effects in RCCPM, then the tool cannot be deployed to find reliable answers to the other sub questions and the main research question.

Sub question 2 is important as the abilities to effectively include, estimate, assess and manage risks and uncertainties are needed to reduce the listed causes of project failure. Taking those risks and uncertainties into account should result in a more accurate estimation of time and costs. Risks and uncertainties relevant to ship & offshore projects, such as those performed at the yard of Damen Verolme Rotterdam, will be used.

For sub question 3 it will also be a challenge to determine the amount of contingency to remove from the tasks and the corresponding method of calculating the buffer size. It would be possible to use MC simulation for buffer sizing, although other, simpler methods will be investigated as well. Another part is to find out the ability of RCCPM to deal with events during the project. It is also believed that buffer management with a fever chart provides an easier way of monitoring and controlling projects, than earned value management.

The answer to sub question 4 is important to know, as lead-time reduction is perhaps the biggest promise of CCPM. Part of this is also the promise of CCPM to reduce time-consuming behaviours such as procrastination and multitasking.

Sub question 5 is designed to know if RCCPM is applicable to the maritime industry. Thereby it is important to know if RCCPM is a uniform method for all kinds of industries and projects or limited to specific ones. The two relevant kinds of projects in this research are the typical complex special projects DVR executes at its yard and the designed serial production process for offshore wind turbine foundations.

Sub question 6 also includes the question to which extent traditional processes should adapt to fit RCCPM. Thereby it is important to know what kind of data is needed to work with RCCPM and if this data is normally available or if it requires extra effort. It is also important to know if an organisation is open for these kinds of changes in working, which team roles are needed and the amount of resistance workers can have. However, the focus of this sub question will not be on this last point, but some literature study can be done to say something about it.

1.5 Scope

The author advocates to not apply ‘pure’ CCPM, but instead to add other useful techniques to CCPM to improve project performance even more. Such a tool is developed during this study. In this research, the techniques listed below are included:

- Monte Carlo (MC) simulation
- Event Chain Methodology (ECM)

Including these techniques will add enhanced functionalities for including, estimating, assessing and controlling risks and uncertainties. This new approach is called RCCPM (Risk-based Critical Chain Project Management) in the later parts of this report. CCPM (without the additions) is used mostly in the literature review.

Change management, resistance to change and implementation of (R)CCPM into an organisation is out of scope for this project. Requirements for improvements will be found, but the approach of how to successfully implement it into an organisation will not be dealt with. It would make the thesis too big and knowledge would be needed that is too much distant from the standard educational program. Moreover, there have already been done studies into this field (Repp, 2012; Verhoef, 2013).

The amount of programming work for the development of the tool will be limited to a minimum. Programming itself will not bring any value to the research project, but does take costly time. If there is any existing software available that (partly) complies with the requirements, then use will be made of that piece of software as far as possible. To make it specific, 'the tool' might end up to be a combination of different software packages, partly existing software and partly programmed by the author. In that case a clear flowchart will be provided, describing what to fill in where and the connections between the different parts.

The focus of this research will be on time, not on costs. Risks and uncertainties will be included, estimated, assessed and controlled in the time planning not in cost estimation. Of course, the time needed to do the projects does say something about the costs, especially labour costs, but it is not much connected with other cost types such as material and equipment. If this research proves to be successfully able to better plan and control risks and uncertainties, then this will certainly lower the costs of a project. The general method to calculate the contingency time can also be used to calculate the contingency budget.

1.6 Methodology

Answers to the main and sub research questions are provided by means of five different activities.

1. A literature review into CCPM.
2. A study into the experiences of other organisations with CCPM.
3. Developing a RCCPM tool.
4. Applying the developed RCCPM tool to a set of case studies and comparing this with the traditional approach, both for lead-time reduction and difference in progress reporting.
5. A survey on the RCCPM type of progress reporting compared to traditional progress reports.

At the end of each of those five activities, the results obtained will be discussed and all results together will be combined at the end to provide answers to the research questions.

1.7 Report Structure

This report is structured by following the methodology as explained in the previous sections and resembles the chronological order of the work done for this research. Chapter 2 shows an extensive literature review into the most often used CCPM literature, followed by a study into the experiences of other organisations with CCPM. Chapter 3 describes the development of a RCCPM tool, which will be applied to a set of case studies in chapter 4. Chapter 5 discusses the results found throughout this research and provides conclusions and recommendations.

2. Literature Review

The preceding chapter showed that Critical Chain Project Management (CCPM) is the solution direction chosen in this study to improve project performance. CCPM is an alternative method of managing projects and is the PM application of the Theory of Constraints (TOC) as introduced by Goldratt (1984, 1997) in his books “The Goal” and “Critical Chain”. This chapter will explain some more about this methodology, and will make its differences as compared to traditional PM explicit. For a complete overview of CCPM the book Critical Chain Project Management by Leach (2014) can be recommended. Since the publication of “Critical Chain” in 1998 till half 2014 there have been 140 English journal and conference papers about CCPM (Ghaffari & Emsley, 2015).

According to Herroelen, Leus, & Demeulemeester (2002) the fundamentals of CCPM are:

- 50% probability activity duration estimates
- No activity due dates
- No project milestones
- No multitasking
- Scheduling objectives are:
    - Minimise makespan
    - Minimise work in progress
- Determine a precedence and resource-feasible baseline schedule
- Identify the critical chain
- Aggregate uncertainty allowances into buffers
- Keep the baseline schedule and the critical chain fixed during project execution
- Determine an early start-based unbuffered projected schedule and report early completions (apply the roadrunner mentality)
- Use the buffers as a proactive warning mechanism during project execution

This chapter will start by identifying the foundations of CCPM in section 2.1. In the second and third section, the CCPM planning and execution processes will be explained, while section 2.4 will point out the changes in these processes in the case of a multiple project environment. Section 2.5 will give the academic viewpoint on how to implement CCPM, followed by a theoretical overview of the differences between CCPM and traditional PM in section 2.6. Other applications of CCPM are shown in section 2.7. Overall conclusions from literature can be found in section 2.8, followed by critics from academics in section 2.9 and suggestions for further research in section 2.10. Section 2.11 will deal with real life experiences of organisations that implemented CCPM.

2.1 Theories Used as a Foundation of CCPM

There are three theories which are used to lay the foundation of CCPM, those are (Leach, 1999):

1. Theory of Constraints (TOC)
2. Common cause variation
3. Statistical laws governing common cause variation

Each one of them will be explained in the subsections below.

2.1.1 Theory of Constraints (TOC)

TOC is a theory by Goldratt originally applied to production systems and written down in his business novel The Goal (Goldratt, 1984). A keyword in TOC is focus and five steps are made to achieve this focus (see Figure 8).

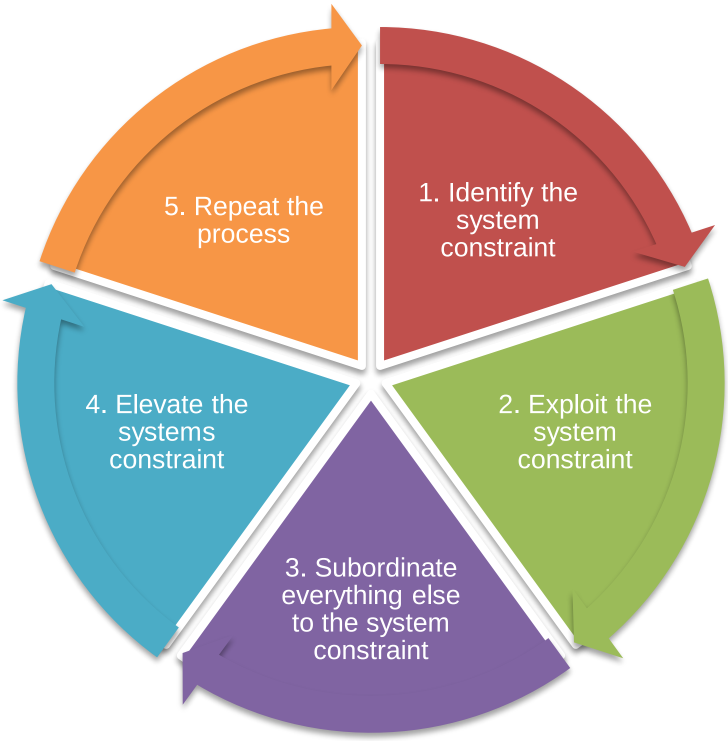

Figure 8: TOC process

Goldratt analysed projects with TOC, leading to his conclusion that most projects fail because of “the failure to effectively manage uncertainty”. This report will not elaborate further on TOC, as TOC is a well-known theory amongst production organisations and academics and a lot of easy to find literature has already covered this subject very well, such as Dettmer (1997), Goldratt (1990) and Rahman (1998).

2.1.2 Common Cause Variation

This theory is made famous by Deming (1986) as “an understanding of variation”, it is one of his four points of profound knowledge. Two types of variation can be identified:

1. Common cause variation; variations inherently related to the overall project.
2. Special cause variation; variations related to a specific (set of) worker(s), machine(s) or location(s).

Common cause variation in projects can be found in the uncertainty of activity durations. Activities are dependent upon each other, mostly by start-finish relations, and therefore the whole projects have statistical variations and events that influence an entire chain of activities. This common cause variation is illustrated in Figure 9 showing the typical activity duration distribution. The solid line shows the probability of a given time, while the dotted line shows the cumulative probability of finishing in less time than or equal to the time on the x-axis. The coloured lines show the 50%, 90% and 95% probability of finishing on time. It can clearly be seen that the distribution has a big left skew and tail to the right. Monte Carlo simulations can be used to estimate uncertainty, but according to Leach (1999) “they do not pose an effective systematic method to manage it”.

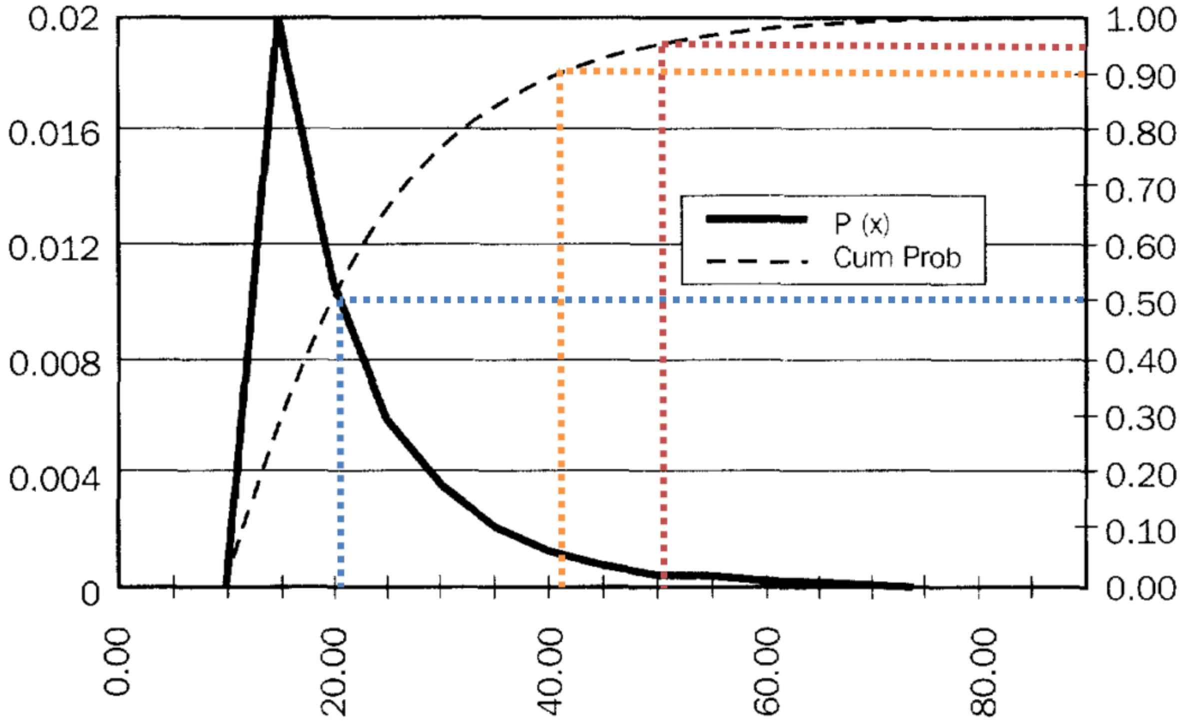

Figure 9: Typical activity duration distribution (based on Leach, 1999)

2.1.3 Statistical Laws Governing Common Cause Variation

The statistical law of aggregation, as described in the PMBOK guide, is stated as “the project variance is the sum of the individual activity variances” (Project Management Institute, 2013). By combining variances, a chain of activities can be protected at the same contingency level, but by using less contingency time (in literature this is often called safety time) than by protecting each individual activity, thus meaning a substantial reduction of the overall estimated duration for a chain of activities (see Figure 10). Steyn (2001) concludes, “Aggregating project schedule contingency reserves is not common practice in traditional PM and applying the principle of aggregation could contribute significantly to the practice of PM”.

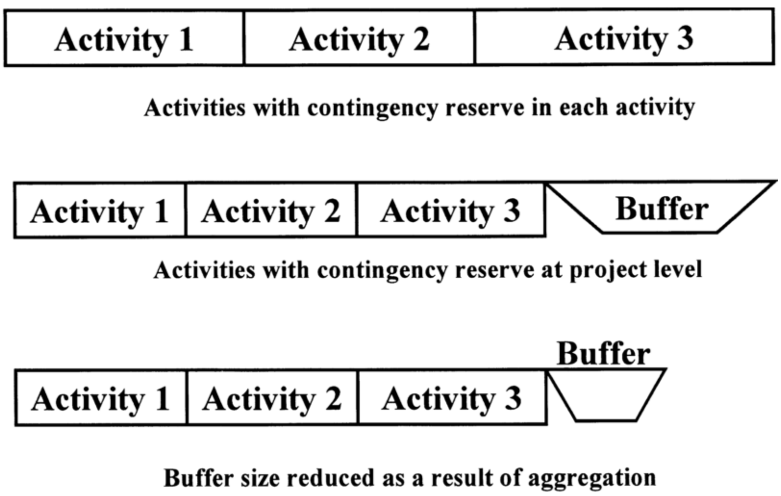

Figure 10: Reduction of project duration as a result of aggregation (Steyn, 2001)

A second statistical law is the central limit theorem stating that "as sample size increases, the distribution of the sample mean becomes closer to the normal distribution" (Rosenblatt, 1956). This means that a chain of activities has a more symmetrical distribution instead of the asymmetrical one for individual activities as depicted in Figure 9 and the more activities on the chain, the more contingency time can be reduced (see Figure 11). This is the same technique as used in the insurance industry, where insurance firms hold a reserve that is much less than the sum of all their client's reserves as it is highly unlikely that every client will be hit by an event at the same time.

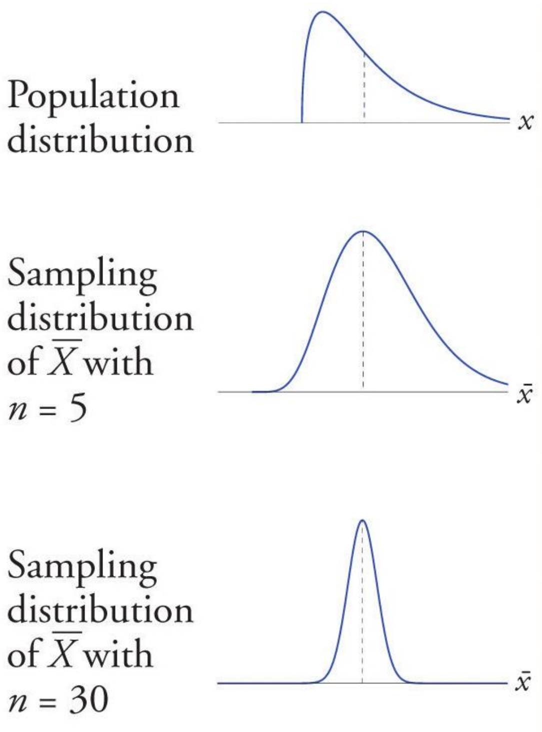

Figure 11: Distribution of population and sample means (Schmitz, 2012)

As an example and demonstration of the equations, suppose n persons need an insurance of their assets each worth €k. Obviously, if individual people have to protect itself against a loss of their assets, the total amount needed is €$n * k$. In case of an insurance firm, it seems clear that less is needed, as a simultaneous loss of all people's assets is highly unlikely. This is what the central limit theorem tells us (Steyn, 2001); if n independent probability distributions with the same variance V are summed together, then:

$$V_{\Sigma} = n * V$$

where V_{Σ} is the variance of the sum. The standard deviation σ is an indication of risk and because $\sigma^2 = n * V$:

$$\sigma_{\Sigma} = n^{\frac{1}{2}} * \sigma$$

where σ_{Σ} is the standard deviation of the sum. Therefore:

$$\sigma_{\Sigma} < n * \sigma$$

This shows that a sum of all risks in a project buffer is less than the sum of all risks that are placed in each individual task, as $n^{1/2} < n$. It also shows that the more risks are aggregated, the more time is gained.

2.2 Critical Chain Planning Process

The critical chain planning process can be described with the steps below (Leach, 1999). It will show the use of three different kinds of buffers; project, feeding and resource buffers.

2.2.1 Identify the Critical Chain

The critical chain is identified by Goldratt (1997) as "the sequence of dependent events that prevents the project from completing in a shorter interval. Resource dependencies determine the critical chain as much as do activity dependencies". Wiest (1964) already introduced a similar concept before, called the critical sequence "determined not by just technological ordering and the set of job times, but also by resource constraints". The critical chain is identical to the critical path if there are no resource constraints. In reality however, there are often resource dependencies in the project planning, which are overlooked by using the critical path (see Figure 12). Organisations that want to keep using critical path and their current software can use resource-levelling algorithms to get closer to the critical chain, given the fact that the software knows how many resources there are available, which is not the case if project are scheduled with unlimited resources.

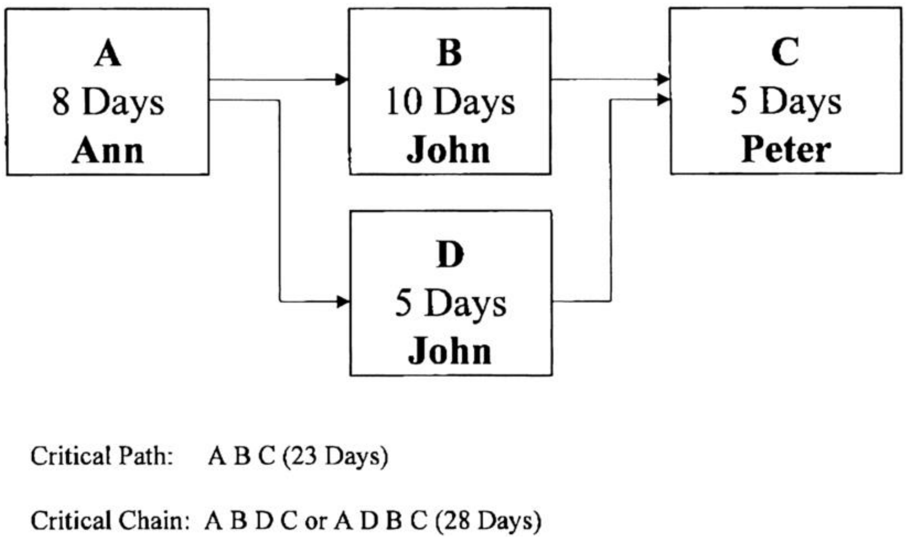

Figure 12: The difference between the critical path and the critical chain (Steyn, 2001)

Herroelen et al., (2002) see the fact that CCPM "explicitly recognizes it is the interaction between activity durations, precedence relations, resource requirements, and resource availabilities that determine the project duration" as one of the fundamental merits of CCPM. Different to the critical path, the critical chain does not change during project execution. In case of multiple critical chains Goldratt (1997) argues that it does not really matter which critical chain is chosen, while Leach (2014) and Newbold (1998) do care about it and also see it as a strategic decision instead of just a mathematical necessity. It could be beneficial to investigate the possibility of using Monte Carlo simulation for selecting the critical chain.

2.2.2 Project Activity Estimates

In the project plan, the 50% probable activity estimates are used. The schedule is first made by using the traditional 90-95% probable estimates. Leach (1999) recommends to "teach the estimators to understand variation and the critical chain method, including assurance that they will not be criticised or otherwise impacted by either underrunning or overrunning the estimated duration". Afterwards the mean (50% probable) durations should be estimated, with the assumptions that there is no multitasking, all inputs for the activity are available at the start and there are no unexpected events. Then the schedule has to be made with these average estimates. Amongst academics there has been a debate on whether this average should be the mean, median or mode; an experiment showed that the use of the mean provided the safest estimate and required the least rescheduling operations (Herroelen & Leus, 2001). The mean will thus be used in this research and the RCCPM tool. The difference between the 90-95% (later called low-risk duration) and 50% probable estimates will be used to estimate the buffer sizes.

2.2.3 Late Start Planning

CCPM uses late start for all project activities instead of the usually default early start. This does not mean there is directly a problem in case of a delayed activity, as project and feeding buffers are placed into the schedule. Using a late start schedule has some advantages over early start (Herroelen & Leus, 2001; Leach, 1999; Steyn, 2001):

- The impact of changes on already finished activities is reduced
- The project cash outflow is delayed
- There is more focus at the start of the project
- An activity is started when it is needed, people know there is no slack available (except for the buffers)
- It decreases the WIP

Steyn (2001) compares this with the advantages of the successful implementation of the just-in-time (JIT) approach in production environments.

Computational experiments of scheduling with the most often used simple priority rules reveal that latest start time and latest finish time rank among the best (Kolisch, 1995). Another experiment among seven project planning software packages on 160 test instances showed that Primavera Project Planner delivers the best resource-constrained scheduling performance, especially in a multi-project environment (Kolisch, 1999).

2.2.4 Project Buffer

The project buffer (PB) is placed at the end of the critical chain, to protect the overall project delivery time (i.e. the due date promised to the customer). This project buffer is smaller than the sum of the cut-away contingency times, because of the central limit theorem. Herroelen & Leus (2001) agree with the use of buffers; "the idea of protecting a deterministic baseline schedule in order to cope with uncertainties is sound and appeals to management". Buffers are placed in the schedule as activities with no assigned work.

2.2.5 Feeding Buffers

The critical chain is protected from delays of other (feeding) paths by placing a feeding buffer (FB) at the end of each path that leads to the critical chain. It also allows activities on the critical chain to start early in case the project is moving well ahead (Herroelen & Leus, 2001). Hoel & Taylor (1999) showed that a non-critical chain could become part of the critical chain in case the feeding buffer exceeds the available slack.

2.2.6 Project and Feeding Buffers Sizing Methods

There are multiple methods available in the literature to calculate the needed buffer size. All methods make use of the difference (D) between the safe 90-95% (S) and average 50% (A) probable estimates.

$$D_i = S_i - A_i$$

2.2.6.1 50% rule

Goldratt (1997) proposed the simplest method; sum the Ds of all activities on the critical chain and use half of that. It assumes a linear relation between the size of the buffer and the length of the chain. Experiments showed that this method leads to larger buffers then necessary (Herroelen & Leus, 2001). This is undesired as it could lead to uncompetitive proposals and thereby loss of potential projects.

$$\frac{1}{2}\sum_{i=1}^{n} D_i$$

2.2.6.2 SSQ Method 1

This method is named Square Root of the Sum of the Squares (SSQ) and is developed and applied by Lucent Technologies (Leach, 1999). Some sources (Newbold, 1998) call it the Root Square Error Method (RSEM). It uses the square root of the sum of the squares of Ds. This method generally leads to smaller buffers and is more effective in getting buy-in than the 50% rule as you do not just cut the given estimates, but use them to calculate the buffer size. This method assumes the project activities are independent (Herroelen & Leus, 2001).

$$\sqrt{\sum_{i=1}^{n} D_i^2}$$

2.2.6.3 SSQ Method 2

Newbold (1998) proposed a follow-up method of the SSQ, which assumes a lognormal distribution of activity durations. He claims that the D will be about 2 standard deviations and assumes that the buffer should be 2 standard deviations long as well. Herroelen & Leus (2001) showed however that this assumption of having about 2 standard deviations all the time is not true.

$$2 * \sqrt{\sum_{i=1}^{n} \left(\frac{D_i}{2}\right)^2}$$

2.2.6.4 Alternative Complex Methods

Tukel, Rom, & Eksioglu (2006) proposed two more methods as an alternative to the above stated well-known buffer sizing techniques. They showed with a simulation experiment that those methods generally provide a smaller buffer, while still meeting the expected 90% probability of an on time delivery. These new methods take project complexity and resource tightness into account. It could be questioned whether these methods are applicable into real world project planning environments as they use data that is generally not available. The two methods are called adaptive procedure with resource tightness and adaptive procedure with density.

2.2.6.5 Monte Carlo Simulation

Some articles refer to Monte Carlo (MC) simulation as a useful technique to estimate the needed buffer size, but have not yet applied it (Geekie & Steyn, 2008). MC simulation will be used in this research, as it is the most elaborate method to estimate the uncertainty in project activities. More about MC simulation is described in subsection 3.3.1.

2.2.7 Resource Buffers

The resource buffers protect the critical chain from resource unavailability. These buffers do not take time in the schedule and can be seen as signals (flags) to ensure the needed resources are available when needed. They are placed if a resource has an activity on the critical chain and the previous activity is done by another resource.

2.3 Project Execution

The project execution in a CCPM project is done by using a so-called roadrunner mentality. The previously introduced buffers are used to monitor and control the project. There is a debate amongst academics on whether or not to reschedule during project execution.

2.3.1 Relay Race Approach

CCPM tries to eliminate date-driven behaviour by only communicating the start dates of activity chains and the end date of the project buffer. Thus all due dates of individual activities are eliminated. This should help to focus on completing the project as fast as possible. The schedule gives approximate start times and estimated durations for all activities. It is not bad if the estimated durations are frequently overrun, as it is expected that 50% of the activities will. In other words, there should not be a blame culture for not finishing on time, in order to encourage everyone to give realistic estimations. The other 50% should be finished on or before the estimated duration. It is expected that work is done according to the "relay race approach" or "roadrunner mentality", which entails (Herroelen & Leus, 2001; Leach, 1999):

- Start the activity as soon as the input is available
- Do not multitask, focus on one task only
- Pass on the output as soon as the activity is completed

Herroelen & Leus (2001) call this semi-active timetabling; "timetabling is semi-active if in the resulting schedule there does not exist an operation which could be started earlier without altering the processing sequence or violating the technological constraints and ready dates".

Herroelen & Leus (2001) have some doubts about the implementation of this mentality, which results in two different schedules; one with the buffers, late start based activities and not updated during execution (the baseline schedule), the second does not take buffers into account and is early start based (the projected schedule). These two different schedules can make communication to the workers more difficult. Parkinson's Law could play a role again if workers see the difference between these two schedules.

Steyn (2001) advocates to include subcontractors in the project's roadrunner mentality with "incentives for early completion of critical activities".

2.3.2 Buffer Management

The buffer consumption rate is used to monitor and control project performance. This is made visual with the use of a fever chart (Figure 13). The fever chart is a simple, but effective visual management instrument to show the buffer situation of a project to those involved. Both project and feeding buffers are managed. The buffer consumption rates will be monitored frequently, at least on a weekly basis. The buffers are updated as often as is needed for the monitoring and is done by asking the performers of the activity how many days (or hours) they estimate until completion of the activity. There are three decision levels:

1. Green zone: no action needed, the project is expected to finish on or before due date.
2. Yellow zone: analyse the cause(s) of the buffer use and set-up a mitigation plan.
3. Red zone: execute the plan.

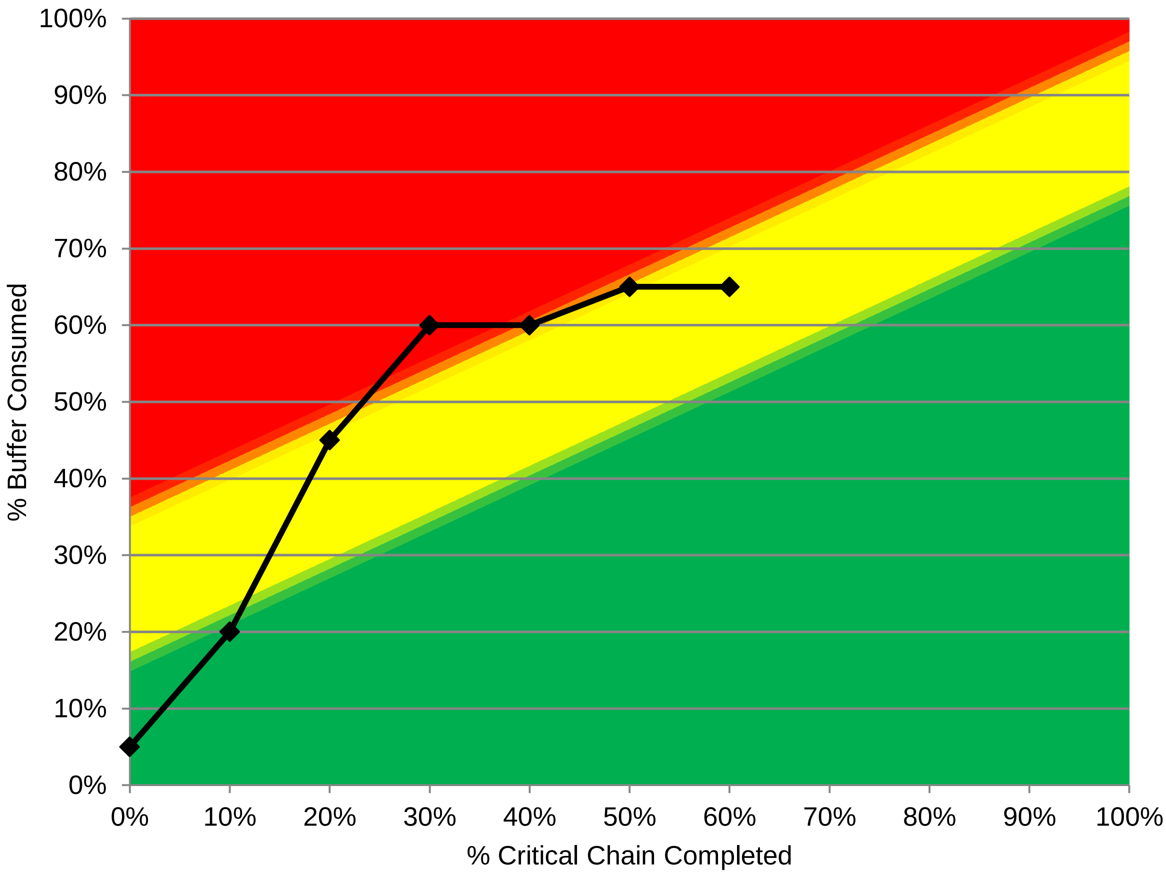

Figure 13: Fever chart

Hu, Cui, & Demeulemeester (2014) have described the calculations behind the fever chart. The following definitions are used:

h	a chain; $h = 1,2,3, \dots H$ with $h = 1$ being the critical chain
H	number of chains
N	number of (non-dummy) activities
n^h	number of activities on each chain
I_j^h	the jth activity on chain h $(1 \leq j \leq n^h, 1 \leq h \leq H)$
BS^h	the size of PB or FB for chain h
$D_B(i)$	the baseline duration of activity i
$D_R(i)$	the realised duration of activity i
$S(i)$	the planned starting time of activity i
$s(i)$	the realised starting time of activity i

The buffer consumption of each individual activity can be calculated with the formula below, also given in words and visualised in Figure 14:

$$BC_j^h = \left(s(I_j^h) + D_R(I_{tj}^h)\right) - \left(S(I_j^h) + D_B(I_j^h)\right)$$

Buffer consumption of each activity = (realised starting time of that activity + realised duration of that activity) - (planned starting time of that activity + planned duration of that activity)

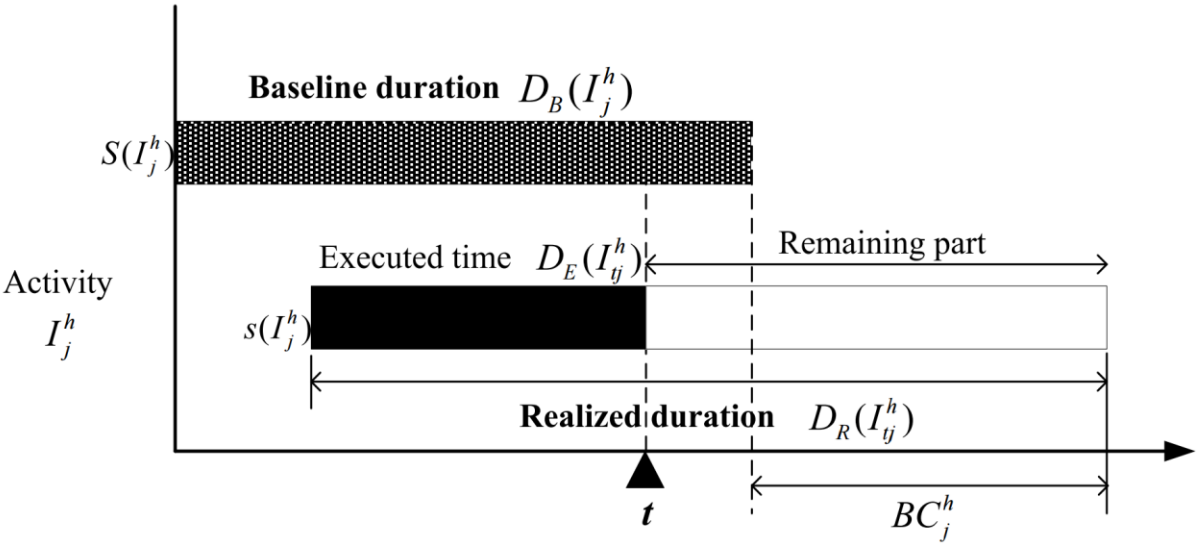

Figure 14: Activity execution status at time *t* (Hu et al., 2014)

Subsequently, the percentage of buffer consumed (PBC) and the percentage of (critical) chain completed (PCC) can be calculated by means of:

$$PBC = \frac{BC_j^h}{BS^h}$$

$$PCC = \frac{current\ execution\ time}{estimated\ project\ completion\ time} = \frac{\left(\sum_{i=1}^{j} D_B\right)(I_i^h)}{\sum_{i=1}^{n_h} D_B\left(I_i^h\right)}$$

The two buffer threshold lines between the coloured zones are defined as:

$$PBC > a_1 + b_1 * PCC$$

$$PBC > a_2 + b_2 * PCC$$

where a_1 and a_2 are the intercepts and b_1 and b_2 the slopes.

Lastly the relative buffer consumption index (RBCI) can be calculated (Hu, Cui, Demeulemeester, & Bie, 2016):

$$RBCI = \frac{PBC}{PCC}$$

The RBCI indicates the project schedule performance. A RBCI that is smaller than 1 means an expected on-time delivery, as the buffer will not be completely consumed. Conversely, a RBCI greater than 1 indicates an expected delay of the project as the buffer will not be big enough; the rate of buffer consumption is greater than the rate of progress on the critical chain.

Hu, Cui, & Demeulemeester (2014) also made a mathematical model to estimate the costs of expediting activities based on buffer management.

2.3.3 Rescheduling

Newbold (1998) and the CCPM method in general, advice not to reschedule to soon; only if the project buffer is in the red part of the fever chart. However, events during project execution can change the critical chain and may result in having one of the other sequences becoming longer than the critical chain (Herroelen & Leus, 2001). In the CCPM method rescheduling is believed to change the focus of the project team and would easily result in over adjustment, as has been proved with the funnel experiment in process control (Deming, 1986). An experiment by Herroelen & Leus (2001) however, showed that staying focused on the critical chain, while this sequence is not critical anymore has harmful effects on the final project delivery date.

2.4 Multiple Project Process

It is important to consider the process in case of multiple projects as it is estimated that about 90% of all projects are carried out in a multiple project environment (Turner, 2009). Most planning and execution processes remain the same in a multiple project environment, however the process changes somewhat to eliminate multitasking and to create a pull system for the projects. Those additions are described below.

2.4.1 Identify the Constraint (Drum)

The constraining resource in an organisation is called the “drum”. This drum sets the beat for all projects. The projects are synchronised to this constraint and capacity buffers are placed between the projects to ensure that the drum resource is available for the next project. This makes it a pull schedule system, because the sequence of projects is made according to the drum capacity. Drum buffers are placed in the schedule to ensure that the drum activities can start earlier in case the drum resource becomes available earlier.

Raz, Barnes & Dvir (2003) doubt the applicability of the drum. They believe that at every point in time, there could be multiple constraining resources and these could change over the course of the projects. Therefore, it would make no sense to fix one single resource as constraint.

2.4.2 Resource Allocation

Resources are allocated according to the following priority rules:

1. Activities in the critical chain over those in the noncritical chains
2. Activities in project chains with the highest project buffer consumption
3. Activities in project chains with the highest feeding buffer consumption

2.5 CCPM Implementation

Steyn (2001) argues that the advantage of CCPM is that it is “simple and can be taught to project staff within a relatively short time. The approach therefore lends itself to be widely applied within organisations, provided that the paradigm shift could be made that (except for the project due date) schedules indicate targets and not commitments”. In addition, CCPM “changes the way we think about project scheduling. A major problem when implementing CCPM is that it implies a paradigm that is radically different from the prevailing one. It would, however, be unrealistic to expect improvement without change and change invariable leads to resistance”.

Raz et al. (2003) distinguish two major sources of cost that one has to take into account with implementing CCPM, namely: software tools and culture change. They argue, “The costs of acquiring, deploying and applying software that support CCPM are likely to be secondary relative to the costs resulting from the need to change the culture of the organisation”. Raz et al. (2003) advice to implement CCPM “if your organisation lacks effective project planning and control processes, you run a relatively large number of quite similar projects in a matrix environment, and your main concern is meeting deadlines, CCPM could be beneficial. Otherwise, the authors suggest carefully weighing the limitations of CCPM and its costs against the potential for contributing to the long-term business success of your organisation. Perhaps the optimal solution is to incorporate those CCPM principles that are applicable to your environment within a broader conventional PM methodology”.

Lechler, Ronen & Stohr (2005a) conclude, “While the application of CCPM is complex, many of its ideas can be easily adapted by practicing managers”. Lechler et al. (2005a) have an idea about why CCPM is still not used so often. They argue that the greatest advantage of traditional PM is the fact that it is a well-established method, and the “training and infrastructure costs needed to change to a CCPM approach are considerable”. They also spoke with some firms that had difficulties with implementing CCPM, specifically with “convincing managers of the efficacy of the approach and getting them to impose the necessary management discipline – for example, to insist on activity times with no contingency margin, to impose priorities on projects, and to develop an environment that eliminates bad multitasking”. In another article the authors advocate a simplified version of CCPM that only uses the project buffer, as their case studies showed that project managers had difficulty with managing the multiple feeding buffers (Lechler, Ronen, & Stohr, 2005b).

Lechler et al. (2005a) identified four management practices from CCPM that can be implemented right away, which are summarised in Table 1.

Table 1: Management practices for direct implementation (Lechler et al., 2005a)

Management practice	Implementation
Manage constraint resources to avoid or solve resource conflict	Monitor closely the constraint resource and solve resource conflicts dependent on the constraint resource.
Reduce WIP	Reduce number and size of active work packages.
Reduce multitasking	Hold regular project meetings, prioritize activities and ensure that no person has more than (say) three or four concurrent tasks. Avoid pre-emption of active tasks.
Focus on total systems throughput rather than individual projects	Prioritize projects. Recognize the bottleneck resource and synchronize its use by different projects based on their priority.

Doyle (2010) developed three “games” to teach all those involved about CCPM, which can be used when implementing CCPM in an organisation. Another useful help in getting a team of people involved are Japanese “safety bug” animated videos about CCPM, YouTube links are provided in the bibliography (Kishira, 2009). These videos will certainly get a discussion going amongst the project team members. They have been used with the culture change needed for the implementation of CCPM at the Japanese Ministry of Land, Infrastructure, Transport and Tourism.

2.6 Theoretical Differences of CCPM with Traditional PM

This paragraph is included to make the fundamental differences between CCPM and traditional PM clear. The major differences and additions of CCPM to traditional PM are (Leach, 1999):

1. The critical chain is used instead of the critical path. The critical chain includes resource dependencies; there is no difference in case of unlimited resources. Furthermore, the critical chain does not change once the project is being executed.
2. Instead of using activity duration estimates with a 90-95% probability of finishing on time, a 50% probability will be used. All individual contingency times are collected and put into a buffer at the end of the chain.
3. The buffer consumption rate will be used to monitor and control the schedule performance with a fever chart, instead of earned value.
4. In multiple project environments, the constraining resource is identified and projects are planned around this resource (the drum resource).
5. Human behaviour changes in a way to eliminate the use of multitasking and encourage the reporting of early completion of activities.

An elaborated systematic comparison of traditional PM (critical path method) and CCPM has been carried out by Lechler, Ronen & Stohr (2005a). This comparison is executed at different levels, where each level is analysed using a multitude of perspectives, these tables can be found in Appendix 2.

2.7 Applicability of CCPM

CCPM has been applied not just in project scheduling, instead there are a variety of different applications that are published in journals or presented at conferences. A short overview is given below. This overview is not complete as it can be expected that not all applications of CCPM are made public.

- Steyn (2002) applied CCPM/TOC to project risk management. This model "ensures that risks not initially identified as high receive the required attention at the right time".
- Yeo & Ning (2002, 2006) and Wei & Ying (2013) proposed a framework for the integration of supply chain management with CCPM in order to reduce, and improve the management of, risks and uncertainties in EPC projects. Specific applications are the procurement of major equipment and selecting service suppliers.
- A budgeting method called "strategic budgeting", which is applied at an automotive company resulting in a cost reduction of 37.6% without firing personnel (Taylor & Rafai, 2003). It reduces slack in budgets in a same way as contingencies in activity durations are reduced.
- Auditing of companies in the accountancy sector (Yang, 2012).
- Development of a rescue plan for maritime disasters (Yan, Jinsong, Xiaofeng, & Ye, 2009).
- Maintenance period of power plant electrical equipment (Dong, Zhao, Zhou, & Lv, 2013).

This overview shows the versatility of CCPM and indicates that the method can be used in many different settings and organisations.

2.8 Overall Conclusions from Literature

This sections aims to give an overview of the most important overall conclusions about CCPM in the literature.

Leach (1999) concludes that "CCPM improves the focus of the project manager and performers", because of its focus on the critical chain and the existence of buffers which enable the project manager to focus and giving him explicit decision thresholds.

Rand (2000) concludes that CCPM "focuses very much on how senior management deals with human behaviour". This is in contrast to traditional PM that very much focuses on the technical aspects of projects only. Rand is also glad to see CCPM's advice to avoid milestones, as they often lead to delays. Milestones are however such an important part of traditional PM that it "will depend on your understanding of the psychology of the workforce" whether or not to accept avoiding milestones. Lastly, Rand concludes that buffers could be implemented quite easily in existing PM approaches "though there may be unwillingness to cut activity times".

Herroelen & Leus (2001) concluded a literature study by stating that most of the articles they read consider CCPM as "the most important breakthrough in the history of PM". They believe that CCPM's "recognition that the interaction between activity durations, precedence relations, resource requirements and resource availabilities has a major influence on the duration of a project is well-taken and in line with the fundamental insights gained in the project scheduling field". Furthermore they conclude that CCPM caused a "shift from a time-oriented (critical path-based) to a resource-constrained (critical chain-based) view. Daily PM practice was in a desperate need for such a shift in focus". Lastly they conclude that "the methodology of inserting and managing resource, feeding, and project buffers provides a simple and workable tool for setting realistic project due dates and for monitoring the project during execution".

Steyn (2001) also appreciates the focus on human behaviour that CCPM accomplished, "Time management techniques normally neglect human behaviour that could typically be expected during project planning and control. CCPM, on the other hand, attempts to account for certain typical human behaviour patterns during project planning and execution". He also claims that even though not all parts are completely original, CCPM "puts together concepts that have not been put together in the same way before and is therefore considered an innovation". About the future potential, Steyn comments "It is not far-fetched to state that the approach has the potential to spark significant changes in PM".

Millhiser & Szmerekovsky (2012) performed a research about teaching CCPM at business schools, concluding, "CCPM is an appropriate PM methodology for student consideration on the basis of motivating critical thinking, especially about behavioural issues". At most universities however, CCPM is not a part of PM courses.

2.9 CCPM Criticism from Literature

This section covers the main critics amongst academics that studied CCPM.

Herroelen & Leus (2001) argue that WIP reduction is not always an important goal; "In capital intensive projects, cash flow patterns may be the determining factor: incoming cash flows may ask for certain activities to start as soon as possible while cash outlays may ask for certain activities to start as late as possible".

Herroelen & Leus (2001) criticise the order of buffer placement. The project buffer is calculated and placed before the feeding buffers. During project execution however the schedule will contain feeding buffers at every noncritical path. Inserting those feeding buffers could have the result that the critical chain is no longer the longest path, as shown by Rizzo (2002). Herroelen & Leus (2001) also advocate updating the project buffer size during project execution, as the expected due date is likely to change during the project.

Herroelen & Leus (2001) and Herroelen et al. (2002) see a danger in the oversimplified view of CCPM towards scheduling and the resulting pitfalls. McKay & Morton (1998) share this view "We believe that most project managers will benefit from a conscious reflection of what Goldratt has written. However, a danger exists for the project manager who does not understand the necessary preconditions". Pinto (1999) comes with a similar conclusion "My concern lies in the strong potential for many companies, who do not understand TOC's strengths and weaknesses, to latch on it as The Next Big Thing regardless of their particular and unique circumstances". From this, it can be concluded that any organisation who wants to implement CCPM should first make sure that all those involved understand the theory. However, it can be argued if this is just the case with CCPM or with every change in organisational processes.

Raz, Barnes & Dvir (2003) conclude that "although CCPM has a number of valuable concepts, it does not provide a complete solution to PM needs, and that organisations should be very careful about the exclusion of conventional PM techniques". Furthermore, they believe that "CCPM is based on the premise that uncertainty in activity duration is the major factor affecting the ability to complete the project on time. But, there are other relevant mismanagement practices that affect schedule expectations, such as external pressures, internal politics, and distorting estimates to win the project, should also be addressed". These critics are justly and literature that is more modern increasingly sees CCPM as an addition to a commonly known PM standard, such as PMBOK, with CCPM mostly replacing the planning and control processes.

Lastly, there are doubts amongst some academics about the role of human behaviours in CCPM. Steyn (2001) concludes, “Although the assumptions regarding human behaviour are not critical to the validity of the technique, scientifically acceptable evidence to prove the validity of these assumptions would be of value”. Similarly Lechler et al. (2005) argue that “it has yet to be proven that Parkinson’s Law and the student syndrome have a strong influence on the lead times of projects”. Next to that, both Raz et al. (2003) and Lechler et al. (2005a) have their doubts if employees will give their real 50% probable times and not add their own contingency to the estimations they give. These doubts are conceivably, it is therefore regrettable that psychologists have not yet showed interest to investigate those human behaviours in project environments.

2.10 Suggestions for Further Research

Some interesting suggestions for further research are identified in the literature, this section points out the most important ones.

Herroelen & Leus (2001) claim that additional research is needed in the development of “effective and efficient algorithms for the creation of robust baseline schedules” and “powerful mechanisms for warning project managers for emerging problems during project execution that may be harmful for the project due date and which allow for the dynamic evaluation of the criticality of project activities”. Since 2001 however, much research has been done and intelligent algorithms are now part of software packages, such as Aurora-CCPM which uses artificial intelligence (Stottler Henke, 2017).

Raz et al. (2003) are “not aware of any comparative studies that provide scientific evidence to the effect that organisations that have adopted CCPM perform better than organisations that apply a conventional PM methodology”. This would help, no doubt, but such as research is extremely difficult to execute. Alternatively, many organisations have shared their successes with implementing CCPM. A short overview will be given in the next section.

Lechler et al. (2005a) identified a number of questions for further research:

- Is it reasonable to ask that activity durations are estimated with no included contingency margin? Can this practice be sustained?
- Can the tendency for people to multitask be controlled?
- Can project managers handle the complexity of buffer management? This question relates to the amount of project and feeding buffers to be managed.
- Can the additional discipline and knowledge required to successfully implement CCPM be found in the majority of organisations?
- Can the implementation of CCPM be simplified by eliminating the feeding buffers?

2.11 Real Life Experiences with CCPM

This section deals with experiences of companies that implemented CCPM. CCPM is used by different kind of organisations, both in size and in industry. A selection of those cases will be described. This section only covers successes, as failed implementations have not been published publicly. Please be aware that failures in all probability do exist and organisations do not like to share this, but this is not expected to be on a large scale.

2.11.1 Combined Overall Experiences

Raz et al. (2003) argue, “CCPM seems to hold answers to problems that have challenged project managers for many years, and presentations on it are enthusiastically received. CCPM proponents have claimed some dramatic successes, but from the author’s personal experiences, these appear to be mainly in organisations that started out with weak or non-existent PM methodologies”.

Leach (1999) describes, “All projects that have diligently applied CCPM have completed the project substantially under the original time estimate, fulfilled the original scope, and came in near or under the estimated budget. Project durations normally reduce by at least 50% in the first pass, and several companies have taken the early successes to cause further substantial duration reductions”.

Millhiser & Szmerekovsky (2012) state that “the number of case studies of successful project execution due to CCPM is burgeoning and the documented improvements include substantial time savings, profitability, customer satisfaction, and worker enthusiasm”.

Ghaffari & Emsley (2015) concluded a research among 20 case studies by stating that CCPM has shown to be successfully implemented in all kinds of different projects, delivering an average reduction of 40% in project duration. They concluded the benefits of CCPM as following (Ghaffari & Emsley, 2015):

- Productivity increased
- Transparency increased
- Communication and collaboration improved
- On-time delivery rate improved
- Multitasking decreased
- Control and monitoring improved
- Throughput increased
- Work in progress reduced

Realization, a company that helps implementing new PM processes, has a lot of CCPM implementation results on its webpages (Realization, 2017). When gathering all of them, the following quantitative results can be seen (Table 2). The median values provide a more reliable outcome as averages can be highly influenced by outliers. It follows that organisations can perform 44% more projects a year, the on-time delivery rate increases with 34% and the projects are delivered 36% earlier. Naturally, these numbers are estimates and they can vary substantially from case to case.

Table 2: CCPM implementation results from (Realization, 2017)

	Number of projects completed per year	On-time delivery rate	Lead time
Number of samples	24	17	34
Average	+ 59%	+ 71%	- 38%
Median	+ 44%	+ 34%	- 36%

Kendall & Austin (2012) collected the results of over 60 organisations, in different sizes and industries, which implemented CCPM; those results can be found in Table 3.

Table 3: CCPM implementation results from (Kendall & Austin, 2012)

	Number of projects completed per year	Lead time
Average	+ 70%	- 39%
Worst case	+ 15%	- 13%
Best case	+ 222 %	- 78%

2.11.2 Some Selected Experiences

This subsection covers some selected cases to show the kind of improvements CCPM made. Some specific experiences of maritime companies are given, as this is the sector of interest for this research. There are much more experiences published on webpages, such as BeingManagement (2017) and Realization (2017).

The largest known implementation of CCPM is from the Japanese Ministry of Land, Infrastructure, Transport and Tourism (Millhiser & Szmerekovsky, 2012). In 2005, they started with one pilot project on Hokkaido, followed by a series of 15 pilot projects in 2006. Because of the impressive pilot results, the number of projects using CCPM exploded in 2007 to 2523 projects and in 2008 to over 4000 projects. Ultimately, this led to the ministerial decision that from 2009 on all projects should use CCPM, which are about 20000 projects a year.

Three major companies in the Netherlands have published their experiences with CCPM. The first one is KPN consulting, they came to the following conclusions (De Vos, 2011).

- A more equal workload amongst the employees throughout the different phases of the project.
- Increase in the amount of projects performed per year.
- Increase in the amount of projects delivered on time.
- A competitive advantage through the adoption of a state-of-the-art planning method and shorter lead-time of projects.

There are two other major CCPM implementations known in the Netherlands, both for IT projects at insurance company Nationale Nederlanden and IT developer Garansys (Schröder, 2015).

CCPM has been actively applied by the US military. Leach (2014) gives the example “The US Navy and US Coast Guard completed ship repairs in record times also increasing the availability of those very expensive machines, effectively creating new ships out of nothing”. The US naval shipyard in Pearl Harbour, Hawaii has implemented CCPM and obtained good results with the maintenance and repair of submarines (Realization, 2017). The job completion rate went from 94% to 98%; on-time delivery was before CCPM implementation less than 60% and increased to more than 95% afterwards. The cost per job was $5043 and reduced with 33% to $3355, lastly overtime dropped by 49% leading to a $9 million saving in the first year. More specific information can be found in the shipyard’s magazine (Hunt, 2004).

LeTourneau, active in offshore jack-up rig design, engineering and fabrication, has had good experiences with CCPM (Realization, 2017). The time for design engineering went from 15 months to 9 months while production engineering went from 9 months to 5 months. Lastly, the fabrication and assembly lead time dropped from 8 months to 5 months.

Other published applications of CCPM in the maritime sector include the maintenance of a research vessel in Indonesia (Manti, Fujimoto, & Chen, 2003) and the newbuilding of an FPSO at IZAR's Fene shipyard (now Navantia) in Spain (Grasas & Ribera, 2003).

3. Development of a RCCPM Method & Tool

This chapter describes the development of the RCCPM method and the accompanying tool. First, the current PM processes are reviewed; hereafter the main objectives and requirements are stated in section 2. Section 3 describes the included risk analysis techniques in order to strengthen CCPM into RCCPM. Sections 4 and 5 cover the entire process of choosing software for the tool. Next, section 6 describes some main decisions for the development of the tool, followed by an elaboration of the RCCPM tool in the planning phase (section 7) and the execution phase (section 8).

3.1 Current Project Management Processes

This section describes the pitfalls and spaces for improvement in the current project management processes at Damen Verolme Rotterdam as the author sees it. This information is obtained by doing observations and having conversations and discussions with different kinds of people in the organisation. In general, it can be said that most of these are not uniquely for Damen Verolme Rotterdam, but can be found in other companies in the maritime sector as well. This section is included to make sure that the RCCPM method would solve problems and undesired effects that can be found at the company.

The global decision-making process for resources and personnel of the yard is as depicted in Figure 15. A difference is made in three levels; strategical, tactical and operational. The goal of this procedure is to timely identify the need for resources and personnel. The RCCPM method focuses on the project planning.

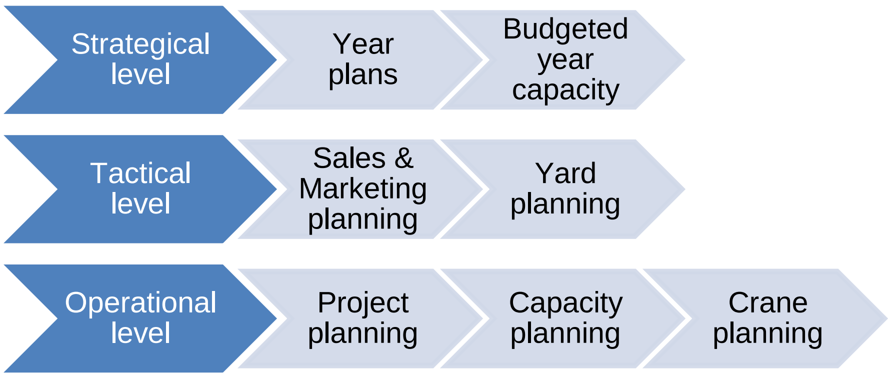

Figure 15: Global decision-making process for resources and personnel

Currently, a schedule is made for each offshore project and big ship projects. Small ship repair projects are not scheduled by the project planner and are also out of scope for this research. Schedules are created for both tender and project execution purposes and a project planner is working on multiple projects at the same time. During the execution phase, the project planner prepares a weekly progress report. The current high-level process flow can be found in appendix 3. This high-level process flow will not change with the RCCPM method as the changes are on a lower level; specifically block numbers 1, 7 and 11 (from appendix 3). Scheduling is currently done as with the critical path method and the same as the traditional PM approach of chapter 2. It also frequently happens that clients specify in the contract that critical path should be used.

Progress reports are made using the earned value method and use the physical % complete per activity. These do not include actuals, so there is only schedule control (no CV and CPI); the progress of an activity is known, but not to which costs. Cost control and reporting is a responsibility of the project accounts department. The actuals are available at the project accounts department, but there is no integration with project planning.

When it comes to the undesired effects that RCCPM aims to eliminate (as written in section 1.3), most of them are applicable at Damen Verolme Rotterdam too except for the concept of adding contingency at multiple layers in the organisation. There is more a top down approach with durations initially coming from the client, which are translated by the business manager into the planning.

Ship repair and offshore conversion jobs are characterised by relative short preparation time and high degree of complexity in technical and operational terms, which also for DVR provides typical project execution challenges. Even though from literature and experiences it can be said that during the real execution of a project, not much control can be done in comparison with the phases before execution (Maylor, 2010). Those controls that are able during execution cost much more money and effort. As an example, it occasionally happens that towards the end of the project there is more work left than estimated, this seems to indicate the presence of the student syndrome and Parkinson's Law. In those cases extra personnel is needed to still meet the contract deadline, costing more money than strictly necessary and decreasing the profit margin.

Interesting for this research is to note that DVR is executing many projects at the same time, which provide typical prioritisation challenges. Such challenges lead to non-value adding activities. Implementing an unambiguous prioritization process, which is part of RCCPM, could significantly improve the effectiveness of the workforce.

3.2 Objectives & Requirements

The main goal of the RCCPM tool is to have the ability to plan and control projects using the CCPM methodology. This tool should give a workable answer to the goal of this research; to find a way to better plan and control projects with a specific focus on the project's risks and uncertainties in order to improve project performance. By developing this tool, the objective is to ultimately achieve the following results:

- Shorten the lead-time of projects.
- Increase the on-time delivery rate; making the completion dates more reliable.
- Increasing the efficiency; complete more projects with the same resources.
- Establish a better work environment; improving the organisation and reduce multitasking.
- A disciplined planning process on which to build future improvements.

This chapter will show how to do this. Specifically, the project plan should:

- Provide clear, stable priorities both within and between projects.
    - Clarity is obtained by having late-start schedules and defined priorities among projects.

    - Stability is obtained by having buffers to account for expected variation.
- Aggregate contingencies to protect projects instead of protecting individual tasks against risks and uncertainties.
- Measure based on global goals instead of local goals. The global bottom-line impact of local decisions should be known.
    - No more silos, but integration of departments and data.
    - No more day-to-day firefighting, but solving root causes.
- Come up with ways to help completing projects faster.

The basis of the solution will be the CCPM methodology. Other useful techniques will be added and are identified in the next section (3.3). Use will be made of already existing software as far as possible. This decision has been made because there are already well functioning software packages that are able to perform parts of the entire RCCPM method. A combination of different software packages will thus be made; this will fasten the overall development process, decreases the change of not functioning software and makes possible future use in the maritime industry easier. The specific software to use in this research will be investigated in the next sections.

Starting point in the development are the schedules, these are the first input for the RCCPM tool. Therefore, this piece of software will be the main building block of the tool. In general, there are two often-used software packages for planning purposes; Primavera P6 and Microsoft Project. The first decision in the development of the tool is between these two packages.

At Damen Verolme Rotterdam, the planning and progress reports are currently made with Primavera P6 Professional. Primavera is also used in many other companies in the maritime industry and will thus be an important option as main building block of the RCCPM tool. Alternatively, Microsoft Project could be used. Schedules from Primavera are easily imported into Microsoft Project. Furthermore, it can be said that Microsoft Project is easier to learn and can thus be easier utilized by more people in the organisation, it is also more used when looked at the entire range of companies. Another important advantage for this project is that Microsoft Project is easier to integrate with other software, because the file format is more versatile. Primavera however has more advanced built-in scheduling techniques. For the development of the tool in this project, the most important points are that it is easy to use and that there are enough possibilities for a straightforward integration with other pieces of software. Microsoft Project scores higher on these points, and will thus be used in the RCCPM tool.

The general list of requirements for the entire RCCPM tool is as following:

- Easy to use and intuitive for both project planners and project managers.
- The entire range of CCPM features should be available.
- The ability to include uncertainties (common cause variations) and risks (special cause variations) in the project schedule.
- The ability to provide a distribution on the probability of finishing a project or activity on a set date.
- To provide a focus and aid in prioritization both in the planning and execution phase.
- Progress reports that are easy to make and that provide a clear overview of the status of a project.

Specific requirements for each piece of software will be presented in the next sections, where also the overview of available software packages and decision of which one to use is made.

3.3 Included Risk Analysis Techniques

The basis of the solution is CCPM. Then a synthesis is made to include Monte Carlo (MC) simulation and Event Chain Methodology (ECM). This end solution is called RCCPM. Risks (special cause variation) and uncertainties (common cause variation) are quantified in order to come up with correct activity durations and buffer sizes. The currently known methods to calculate the buffer sizes, as covered in subsection 2.2.6, are quite rough. The project buffer however could easily take 25% of the project lead-time. This project buffer should not be too small, because the planned end date of the project buffer is the delivery date for the client and the risks of getting fines for late delivery should be avoided. A too large project buffer on the other hand would again lead to human behaviour of using all of it, resulting in uncompetitive proposals. This is why advanced risk analysis techniques will be applied.

Thus, the solution is not just using “pure” CCPM, which is an already existing method. Instead, other techniques are combined with CCPM, making the solution original and in potential better able to cope with the causes of project failure as listed in section 1.2. This section will give an overview of the overall theory and the potential of each technique for the RCCPM tool. The specific functionalities that each technique brings to the tool are combined in an overall flowchart (section 3.7).

3.3.1 Monte Carlo Simulation

Monte Carlo (MC) simulation is a technique to better estimate outcomes by drawing a big amount of numbers from a probability distribution. Additionally, certain events can be included into the simulation such as the probability of bad weather or the availability of equipment and how this affects certain tasks and thereby the complete project. As such, it allows for more informed decision making under uncertainty. The final deliverable is a distribution on the possible completion dates for the project in contrast to traditional deterministic project plans. More can be read in Kwak & Ingall (2007). MC simulation is already applied to traditional critical path planning, but in that case its use is limited to providing an indication of the probability of finishing on time. With critical chain, these results can be fed back into the planning to set the appropriate activity durations and buffer sizes.

3.3.2 Event Chain Methodology

Event Chain Methodology (ECM) can be seen as an addition to “normal” MC simulation, which only focuses on uncertainty estimations of activities and is thus only useful for common cause variation. ECM is a technique for identifying and managing events (both risks and opportunities) that can cause a complete sequence of tasks to be affected by a certain event (Virine & Trumper, n.d.). It is important to know when an event occurs, which can be defined by a probabilistic distribution. If such an event occurs, the “state” of an activity changes; after the event the activity will be performed differently than before. The consequences of this event are dependent on the timing of the event. In addition, it will not only affect one specific task, instead a complete chain of tasks will be affected by the event. This cumulative effect can be quantified by using the previously mentioned MC simulation technique. Afterwards sensitivity analysis will show the crucial activities and critical events that affect the project schedule the most.

3.4 Choice of CCPM Software

This section describes the main requirements for the CCPM software to be used in the tool. The available CCPM software packages are reviewed and compared; thereafter a decision for a software package is made.

3.4.1 List of Requirements

There are some requirements to be met by the CCPM software. An identification of these requirements has been made, and is listed below.

1. Compatibility with Microsoft Project (both import and export).
2. The software developer should provide a free (or low cost) trial, student license or research license for at least four months.
3. The software developer should not require confidential data, a copy of the full report or permission to publish the report, paper or results in part or complete.
4. The software developer should be willing to provide free and timely support by email in case of issues and questions.
5. The software should be easy to use and easy to learn, with an intuitive interface.
6. The software should be well known and applied frequently.
7. The software should be applicable and already applied to large, complex projects.
8. The basic CCPM functionalities should be available, including:
    - A. Identifying and indicating the critical chain
    - B. The insertion of a project buffer
    - C. The insertion of feeding buffers
    - D. The ability to choose the buffer calculation method or set the size yourself
    - E. A fever chart

3.4.2 Identification and Comparison of CCPM Software

There are not a lot of project management software packages or developers that have included CCPM or developed a product specifically for CCPM. After extensive research, eight of such software packages are found:

- Aurora-CCPM by Stottler Henke
- BeingManagement 3 by Being
- CCPM+ by Robbins Gioia
- Concerto by Realization
- Exepron by Exepron
- Lynx by A-Dato
- ProChain by ProChain Solutions
- Sciforma by Sciforma

All eight are taken into consideration and compared based on the requirements as stated in subsection 3.4.1. Requirements 1 to 4 are hard requirements; they have to be met in order to be used in this research. This comparison can be found in Table 4 and forms the first round of selection.

Table 4: Comparison of CCPM Software for Hard Requirements

Name	Aurora-CCPM	Being Management3	CCPM+	Concerto
Developer	Stottler Henke	Being	Robbins Gioia	Realization
1. Compatibility with Microsoft Project	Yes	Yes	Yes, add-in	Yes
2. Availability of a (free or low cost) research license	Requires $500 per month	Yes	Unknown	Yes
3. Acceptability of requirements for license	Requires a copy of the report and permission to publish the results	No requirements	Unknown	Requires confidential data and permission to publish info about the cases
4. Customer support by email	Yes	Insufficient	No response	Insufficient

Name	Exepron	Lynx	ProChain	Sciforma
Developer	Exepron	A-dato	ProChain Solutions	Sciforma
1. Compatibility with Microsoft Project	Yes	Yes	Yes, add-in	Yes
2. Availability of a (free or low cost) research license	Yes	Yes	Yes	Unknown
3. Acceptability of requirements for license	Requires a copy of the results and permission to publish all or part at their discretion	No requirements	Requires copy of the paper only	Unknown
4. Customer support by email	Yes	Yes	Yes	No response

The hard requirements are resulting in only two software programs left; Lynx by A-Dato and ProChain by ProChain Solutions. These two software packages are compared for requirements 5 to 8 (A to E) based on the analytical hierarchy process (AHP) (Saaty, 2008). The AHP involves pairwise comparisons between the software and their strength in meeting each requirement; secondly it compares all requirements with respect to their importance to reaching the goal. Scores are given between 1 (equal strength/importance) and 9 (extreme strength/importance). This leads to priorities for each requirement and each candidate as shown in Table 5. All pairwise comparisons can be found in appendix 4. ProChain has a priority of 0.77, more than three times as much as Lynx.

Table 5: AHP overall priorities

	ProChain	Lynx	Total priority
5. Easy to use/learn	0.23	0.05	0.28
6. Well known and applied frequently	0.04	0.01	0.04
7. Track record for large, complex projects	0.10	0.01	0.11
8.A Critical Chain	0.05	0.05	0.10
8.B Project buffer	0.05	0.05	0.10
8.C Feedings buffers	0.02	0.02	0.03
8.D Buffer sizing methods	0.03	0.03	0.24
8.E Fever chart	0.08	0.02	0.10
Total priority	0.77	0.23	

3.4.3 Selected Software: ProChain

This subsection gives a short introduction to the selected CCPM software program: ProChain (ProChain Solutions, 2017). ProChain has been the first software program to work with CCPM and the focus of the program is on CCPM only; no other scheduling methodologies are used. They have been actively improving their software and currently version 12.3 is the most recent, which will also be the version used in this research. ProChain is fully integrated with Microsoft Project as an add-in; all data is entered and stored within Microsoft Project. Besides the CCPM features, the software also includes a network analysis in order to assess the quality of the schedule.

ProChain claims to be "the leader in PM solutions for Fortune 500 companies". There are more than 150 universities in their public client list. ProChain claims to have delivered the following results:

- 20 – 50 % reduction in actual execution of projects
- 30 – 60 % increase in productivity
- 50 – 200 % increase in project throughput
- Return on investment ratio greater than 100:1
- Significant improvements in quality of life
- Stable and continuous process improvement

3.5 Choice of Risk Analysis Software

This section describes the main requirements for the risk analysis software to be used in the tool. The available software packages are reviewed and compared; thereafter a decision for a software package is made.

3.5.1 List of Requirements

When it comes to selecting the risk analysis software, the same hard requirements as identified for CCPM software apply:

1. Compatibility with Microsoft Project (both import and export).
2. The software developer should provide a free (or low cost) trial, student license or research license for at least four months.
3. The software developer should not require confidential data, a copy of the full report or permission to publish the report, paper or results in part or complete.
4. The software developer should be willing to provide free and timely support by email in case of issues and questions.

Other requirements are:

5. The software should be easy to use and easy to learn, with an intuitive interface.
6. The software should be well known and applied frequently.
7. The ability to execute MC simulations, including
   A. Choosing an appropriate probability distribution (like beta, triangular and normal)
   B. Risks (not only uncertainties) to perform ECM
   C. A clear graph (histogram) showing the distribution of results with numerical values
   D. A sensitivity analysis (incl. tornado chart)

3.5.2 Comparison of Software Packages

After extensive research, five risk analysis software programs have been found that can perform MC simulation and schedule risk analysis:

- @Risk by Palisade
- Full Monte by Barbecana
- Primavera Risk Analysis by Oracle
- RiskyProject by Intaver Institute
- Tamara by Vose Software

All five are taken into consideration and are first compared based on the hard requirements as stated in subsection 3.5.1; they have to be met in order to be used in this research. This comparison can be found in Table 6 and forms the first round of selection.

Table 6: Comparison of Risk Analysis Software for Hard Requirements

Name	@Risk	Full Monte	Primavera Risk Analysis	RiskyProject	Tamara
Developer	Palisade	Barbecana	Oracle	Intaver Institute	Vose Software
1. Compatibility with Microsoft Project	Yes	Yes, add-in	Yes	Yes, add-in	Yes
2. Availability of a (free or low cost) research license	£35 student license	Yes	No, 30 day trial only	Yes, 150 days	Unknown
3. Acceptability of requirements for license	No requirements	No requirements	N/A	No requirements	Unknown
4. Customer support by email	Yes	Yes	Yes	Yes	No response

The hard requirements are resulting in three software programs left; @Risk, Full Monte and RiskyProject. These three software packages are compared for requirements 5 to 7 (A to D) based on the analytical hierarchy process (AHP) (Saaty, 2008). The AHP involves pairwise comparisons between the software and their strength in meeting each requirement; secondly it compares all requirements with respect to their importance to reaching the goal. Scores are given between 1 (equal strength/importance) and 9 (extreme strength/importance). This leads to priorities for each requirement and each candidate as shown in **Error! Not a valid bookmark self-reference.**. All pairwise comparisons can be found in appendix 4. RiskyProject has a priority of 0.62, which is more than double as much as @Risk and five times as much as Full Monte.

Table 7: Overall AHP priorities

	@Risk	Full Monte	RiskyProject	Total priority
5. Easy to use/learn	0.05	0.05	0.23	0.32
6. Well known and applied frequently	0.04	0.00	0.01	0.06
7.A Statistical distributions	0.07	0.01	0.03	0.11
7.B Inclusion of risks	0.03	0.03	0.27	0.33
7.C Histogram with results	0.02	0.00	0.02	0.05
7.D Sensitivity analysis	0.06	0.01	0.06	0.13
Total priority	0.27	0.11	0.62	

3.5.3 Selected Software: RiskyProject

This subsection gives a short introduction to the selected risk analysis software program: RiskyProject (Intaver Institute, 2017). The main advantage of RiskyProject is its ability to also include risks instead of performing simulations based on uncertainties only. This provides a clear distinction between common cause variation and special cause variation. RiskyProject is also able to perform cost risk analysis, next to schedule risk analysis. Intaver Institute is founded in 2002 by executives, economists, mathematicians and computer scientists, from different industries and backgrounds. Together they "believe that advanced technology based on operational research can significantly contribute to PM". Since 2006, they have a university relationship program. More information about the features will be described in the next sections, where the real application of RiskyProject in the RCCPM tool will be covered.

3.6 Decisions for the RCCPM Tool

This section describes all developments and decisions to be made before a flowchart and a step-by-step plan can be presented.

3.6.1 Buffer Types

As described in section 2.2, CCPM has three different kind of buffers; project, feeding and resource buffers (Figure 16). Using all of these types of buffers could easily lead to tens of buffers in projects of the scope of this research. This is in serious contradiction with the aim to deliver focus and prioritisation with the RCCPM method. Therefore, the amount of buffers should be reduced, so there can be a focus.

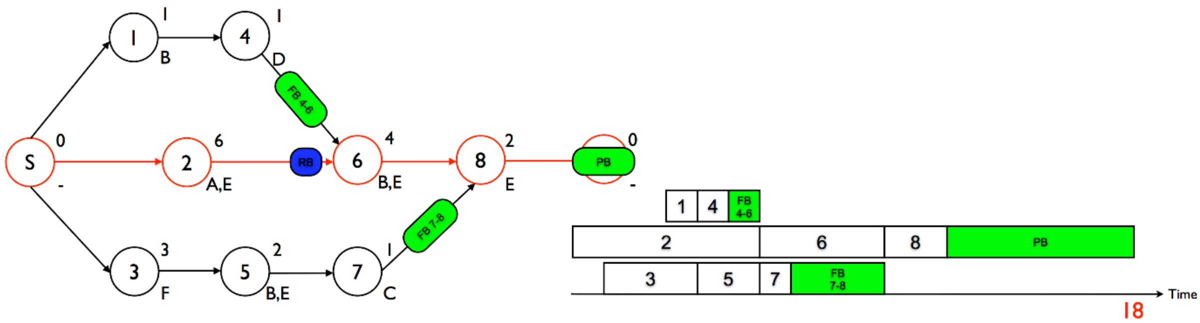

Figure 16: Buffer Types (Vanhoucke, 2012)

Resource buffers will not be used in the RCCPM method, because they are just a notification; there is no duration associated with. They make the schedule more complicated than strictly needed and these notifications are better suited to be communicated during schedule update meetings. Moreover, these kinds of notifications are better suited lower in the organisation, instead of in the global project schedule.

Feedings buffers will also not be used as part of the RCCPM method as the focus should be on the final delivery of the project. This decision is made in order to provide more focus during the control phase of the project. There will be a project buffer for each endpoint of the project. Normally there is only one endpoint, but there are situations with multiple endpoints, such as delivery of an order in multiple batches where every batch has a contract deadline. The concept of feeding buffers however will be used to calculate the project buffer size in the next subsection.

3.6.2 Buffer Sizing Method

The project buffer, which is placed at every endpoint, has to be sized appropriately. Normally, the size of the project buffer is based on a fixed critical chain of activities prior to the project buffer. However, it is too simple to assume that there is only one possible critical chain. Normally there are multiple chains of activities that have a certain chance to become the critical chain. This chance can be used to calculate the buffer size. For example if there are three possible chains which all have a 1/3 chance to become critical, then all three chains are used with a probability of 1/3 each to calculate the buffer size. By doing this, feeding buffers are no longer necessary as the project now is protected to those chains too, instead of one chain only. The criticality index (CI) gives the probability that a task lies on the critical chain and will be used to calculate the buffer size.

The change from one fixed critical chain to a weighted average of multiple critical chains also means that the horizontal axis of the fever chart changes. This will no longer show the progress on a fixed critical chain, instead the same probabilities will be used to show the progress on the weighted critical chain. In the example, the progress on each of the three chains will count for 1/3 each in the fever chart.

As described in subsection 2.2.6, there are multiple methods to calculate the buffer size. The standard in CCPM literature and in ProChain is the 50% rule. There is however, no sound justification for using 50% and research shows that this method generally makes buffers too big. The SSQ method has shown to have the most potential of calculating the appropriate buffer size. This method however very much rely on the mean (M) and high (H) duration estimates. By performing MC simulations, these estimates can be made as close to reality as possible. The next section will show how those MC simulations are done, for now just keep in mind the deliverables: M, H and CI.

For every activity i, the difference between the mean and high estimate is calculated:

$$D_i = H_i - M_i$$

The standard SSQ formula, assuming a fixed critical chain, is:

$$\sqrt{\sum_{i=1}^{n} D_i^2}$$

Adopting this formula to having multiple possible critical chains gives the formula used in the RCCPM method to calculate the buffer size:

$$\sqrt{\sum_{i=1}^{n} (CI_i * D_i^2)}$$

Unfortunately, RiskyProject does not have the functionality of showing the CI. Therefore, the standard SSQ formula will be used in the RCCPM tool. The developers of RiskyProject do not show the CI to the user because an activity that is always on the critical chain (i.e. a CI of 100%) does not always mean that the activity has a big effect on the project completion date. For instance, a start activity of only 1 day will always have a CI of 100%, but will hardly affect the project completion date. Therefore, RiskyProject uses the cruciality index (CRI). The CRI is defined as the correlation between activity duration and the project duration. Specifically, it uses Spearman's rank correlation coefficient; a non-parametric measure of statistical dependence between two variables.

3.6.3 Probability Distribution: Beta

There are a variety of distributions possible, but some of them will not be applicable a lot or are too simplified. This subsection looks at the use of each distribution. An overview of the distributions that are available in RiskyProject along with their probability density function, parameters and usage can be found in appendix 5.

The probability density function should have its maximum value somewhere around the base duration, not at its low duration. Therefore, gamma, exponential, Laplace and Cauchy distributions will not be used. It can also be said that the duration distribution is skewed towards the low duration and has a tail towards the high duration. This eliminates the uniform, normal and lognormal distributions. It is also too simple to say that there is a linear distribution, so triangular is dismissed. Now, four possible distributions are left: beta, beta pert, Gumbel and Rayleigh. The Gumbel distribution is designed to model the extreme values and is therefore not suited as well.

The beta distribution is the distribution from that is usually chosen for project durations (Perez, Martin, Garcia, & Granero, 2016) and will therefore be used in the RCCPM tool. The beta distribution uses two shape parameters: α and β. To obtain a left skewed distribution, α should be greater than β. These parameters could be calculated for each activity by using the low, base and high durations, the mean and the variance. For this method however, fixed values for α (2) and β (4) will be used. After some years use of the tool, these values could be improved based on collected data (planned and actual duration). The distribution has the following probability density function (Figure 17). For special cases, the shape parameters could be changed or another distribution could be chosen. There should not be too much focus on deciding and continuously adjusting the input probability distribution as research has shown that its effect on the output distribution is not significant (Visser, 2016).

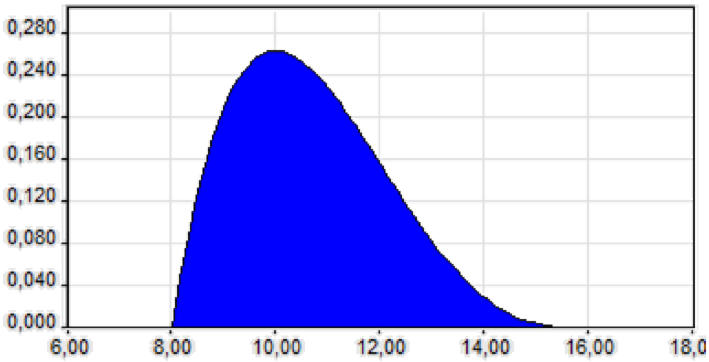

Figure 17: Beta distribution, probability density function

3.6.4 Correlations

Next to the inclusion of risks and uncertainties in schedule risk analysis, one could also choose to add correlations between risks. Those correlations would be another input for the MC simulation and tells in which way the probability of occurrence in a specific simulation round of a certain risk is affected by the occurrence of another risk; it makes the risks dependent upon each other. For instance if risk A occurs the chance that risk B occurs in the same simulation round increases, while if risk A does not occur the chance that risk B occurs in the same simulation round decreases. Risks are assumed independent of each other in case no correlations are used.

Research has shown that making risks dependent upon each other by correlations results in more simulation rounds with either no risks happening or all of the risks happening, while risks occur more evenly spread throughout the simulation rounds without correlations. Therefore, numerical experiments show that including correlations increases the variance of the distribution. However, the mean value of the distribution remains the same as the individual probabilities and impacts are not affected by correlations, as stated by Peleskei, Dorca, Munteanu & Munteanu (2015) and Wall (1997).

The decision is made to not include correlations in the RCCPM tool and later on in the case studies as MC simulation is used to estimate the P50 duration of activities, which is the mean value. Another reason is that including correlations, which are known to be difficult to estimate, could bring in a lot of unnecessary noise in the simulation model. Also in the light of a lean management philosophy including data that does not affect the goal of the task is considered as waste and does not help in the focus RCCPM aims to establish.

3.7 RCCPM Tool in the Planning Phase

This section describes how all software programs work together and which steps a user has to take during the planning phase of a project by providing a flowchart and step-by-step plan. A flowchart with all steps is provided in Figure 18. A description per step is also provided in the text.

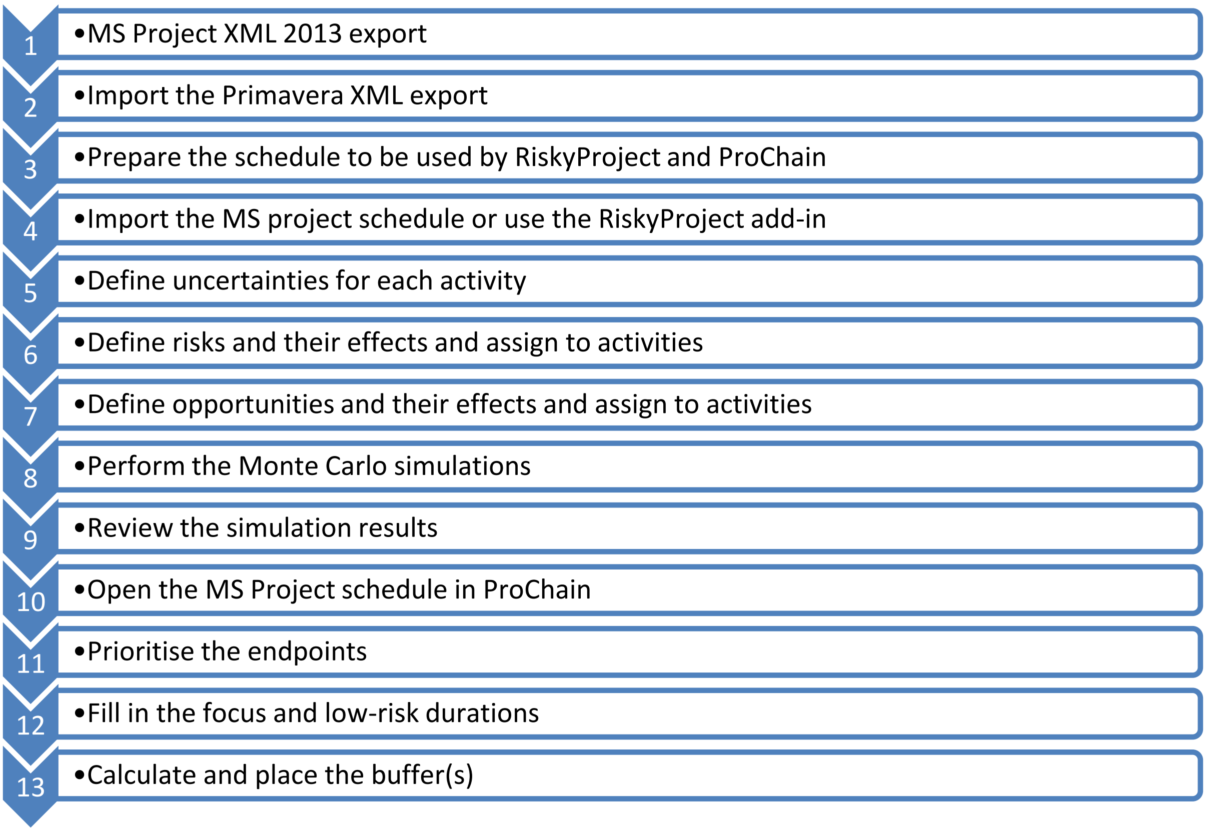

Figure 18: Step-by-step plan for the RCCPM tool in the planning phase

On a system level, there are four important blocks to be identified (Figure 19); Primavera P6, Microsoft Project, RiskyProject and ProChain.

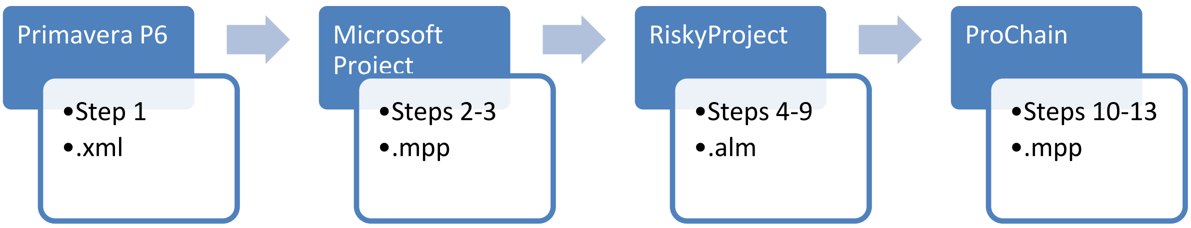

Figure 19: Software flowchart

Primavera P6

Primavera P6 is not strictly needed for this tool, but schedules made with Primavera will be used in the case studies. In case of a new project, the schedule could also be made completely in Microsoft Project to be used for the RCCPM tool.

Step 1: MS Project XML 2013 export

In Primavera P6 the already made schedule is exported as a MS Project XML 2013 file. The basis of the RCCPM schedule is very similar to how a schedule is traditionally made, like inserting all activities according to a WBS structure and linking activities with dependencies. In case of a new schedule, just develop the schedule as you normally do; all changes concerning traditional PM will be described in the following steps.

Microsoft Project

Microsoft Project is used as the as the main connection and data storage software program. Both RiskyProject and ProChain are an add-in to Microsoft Project.

Step 2: Import the Primavera XML export

In MS Project, import the XML export made by Primavera. Choose to import the file as a new project.

Step 3: Prepare the schedule to be used by RiskyProject and ProChain

This step is needed to check if all relationships are included. Every activity needs at least one predecessor. Every activity with no successor is considered an endpoint, and will thus be protected by a project buffer. Checks need to be done to ensure that the calendar from Primavera is correctly translated into MS Project; do not use the standard 8 hour calendar if the project is planned with a two-shift schedule.

Another important preparation is to adjust the schedule from early start to late start. Normally, activities are started as early as possible. However, with RCCPM activities start as late as possible to eliminate undesired behaviour (more in subsection 2.2.3). If there are already buffers, slack or (free) float in the schedule, then these are deleted. They will not be necessary anymore with the insertion of a project buffer.

The last aspect of this step is to have the least milestones as possible. Milestones encourage date-driven behaviour, resulting in adjusting people's effort to the provided time. Instead, the relay race approach should be encouraged.

RiskyProject

In RiskyProject, the uncertainties, risks and opportunities will be defined and quantified using Monte Carlo simulations. Be aware of double counting risk and uncertainty; a risk that is modelled explicitly should not be included in the uncertainty estimations of activities.

Step 4: Import the MS project schedule or use the RiskyProject add-in

The MS Project schedule can be easily imported as an xml file in the standalone desktop version of RiskyProject. Alternatively, one can use the RiskyProject add-in in MS Project where the basic functionalities are available and the desktop version will automatically be opened, with the correct schedule, if needed for more advanced operations.

Step 5: Define uncertainties for each activity

Uncertainties should only be used for common cause variation. Fill in 3-point duration estimates: a low, base and high duration. The low is the absolute minimum time needed, the base is the time needed if everything goes according to plan, with no multitasking and all input available at the start of the activity. The high is with multitasking and on the high side of uncertainty. Not with risks, these are taken into account separately. Choose the beta distribution type, with $\alpha=2$ and $\beta=4$. For special cases, uncertainty can also be defined for the start time of an activity. This process could also be standardised by only entering the base duration and defining the low and high duration as a percentage of the base duration (e.g. 90% and 120%).

Step 6: Define risks and their effects and assign to activities

A risk should be defined and linked to the activities where it has an effect on. Then the probability of the risk occurring should be entered together with an outcome for that risk. The outcome can be different for each activity. Possible outcomes are relative delay (in %), fixed delay (in days) or a restart of the task. Standard, the risk has an equal change of occurring throughout the activity, but this can be changed to only a specific part of the activity or for example a higher change at the start than at the end by using a triangular distribution. Risks can also be assigned to resources (e.g. cranes), if those resources are included in the schedule.

Step 7: Define opportunities and their effects and assign to activities

The same approach as step 6 can be followed to include opportunities to shorten certain activity durations.

Step 8: Perform the Monte Carlo simulation

This is done by RiskyProject itself. The maximum number of simulations is set at 50000 and stop when the mean and standard deviation changes by less than 0.05% over 100 simulations.

Step 9: Review the simulation results

The mean and high duration outcomes of each activity are used in ProChain to set the RCCPM activity durations and to calculate the buffer size. Standard, high is defined as P75, but this can be changed if necessary. This probability is a management decision and could change for every project. A histogram showing a distribution of the possible durations is created for both the entire project as well as each individual activity. The activities that affect the project duration the most are identified by a sensitivity analysis (tornado diagram).

ProChain

ProChain is used for the specific CCPM functionalities of the RCCPM tool.

Step 10: Open the MS Project schedule in ProChain

The first step in ProChain is to open the schedule that was made with step 3.

Step 11: Prioritise the endpoints

This step is only applicable to projects with multiple endpoints. In case of multiple endpoints the user should prioritise each endpoint by assigning a number between 1 (high priority) and 9 (low priority). Prioritising increases the focus and is used in resource levelling to know the relative importance of endpoints.

Step 12: Fill in the focus and low-risk durations

The focus duration (also called mean or P50) is determined with the MC simulation from step 9. The low-risk duration is the duration that was in the traditional schedule. These durations are put into the RCCPM schedule. The focus duration will be used for scheduling the project and defines the size of each activity in the Gantt chart.

Step 13: Calculate and place the buffer(s)

Every endpoint gets a project buffer. The buffer size is calculated by the standard SSQ method as substantiated in subsection 3.6.2.

3.8 RCCPM Tool in the Execution Phase

This section describes which steps a user has to take during the execution phase of a project by providing a step-by-step plan. During the execution phase, only ProChain is used. A flowchart with all steps is provided below (Figure 20). A description per step is also provided in the text. These kinds of progress updates should be performed on a weekly basis for most projects in the scope of this research. Shorter or more complex projects may require more frequent updating.

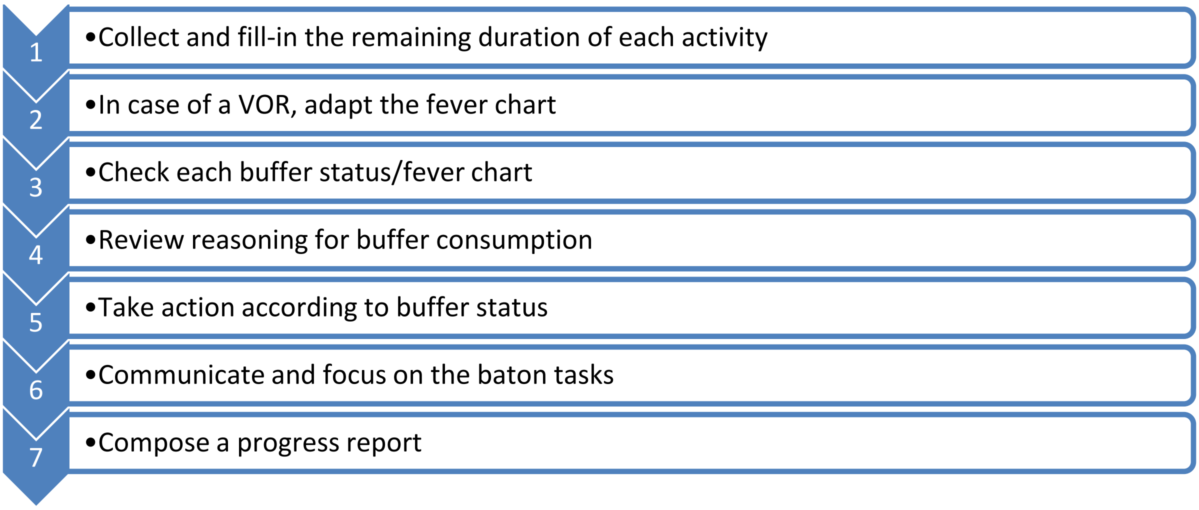

Figure 20: Step-by-step plan for the RCCPM tool in the execution phase

Step 1: Collect and fill-in the remaining duration of each activity

Normally, weekly progress sheets are distributed to the area managers of each project asking the (physical) % of completion of activities. With RCCPM, it is only important to know the remaining duration (in days) of the activities.

Step 2: In case of a VOR, adapt the fever chart

In case of VOR's (more or less work), the fever chart might needs to change. If the added or scrapped work is not part of the critical chain, the fever chart does not change as it shows the progress on the critical chain and buffer can only be used by activities on the critical chain. However, if the work is part of the critical chain; the size of both the chain and the buffer will change. The most convenient way to cope with this is to adjust the sizes of both axes, for instance the % chain complete is extended to 110% and the % buffer used to

115%. By doing this, the history of the data points in the chart stays at the exact same position and the newly added point will not show a drop or increase of the line because of the VOR.

Step 3: Check each buffer status & fever chart

The remaining duration is used to update the buffer status. This buffer status, along with former statuses, is plotted in a fever chart. The calculations for the fever chart are explained in subsection 2.3.2. Another (dashed) line in the fever chart shows the variability profile. This is the amount of buffer that is expected to be consumed at a given % chain complete. The variability is based on the difference between the focus and low-risk durations. If the project has the most variability early on, there is a higher slope early and a lower slope later on. In case the latest status point is above the variability chain, it indicates that more buffer is used than expected based on the variability of the network. However, actions should not be made based on the position with respect to the variability chain. Too frequent and too fast changes in a project would only harm the project by shifting focus and priorities too much. Therefore, actions are only taken based on the colour zone in the fever chart (step 5).

Step 4: Review reasoning for buffer consumption

If an activity consumes buffer (i.e. the remaining duration is more than P50 duration minus used duration) there should be reasoning provided (on the weekly progress sheets) for why it took more time. This reasoning should be stored into a system and used to eliminate further buffer consumption. It is assumed that the obligation of giving a reason for the buffer consumption has a positive effect on the total buffer consumption rate; people should really underpin why they needed more and what they can do to prevent further buffer consumption.

Step 5: Take action according to buffer status

Different kind of actions can be taken, depending on the current colour zone in the fever chart:

- Green zone: the project is ahead of schedule and likely to be delivered ahead of schedule. No extra control actions are needed.
- Yellow zone: the project is on schedule and is expected to be finished at the scheduled date. Small setbacks could result in a delay, so the reasons for buffer consumption should be reviewed and a plan should be made with control measures to counteract delays as soon as they occur.
- Red zone: the project is running behind schedule and is expected to be finished late. The plan with control measures as made in the yellow zone should be executed immediately.

If the project is in the red zone, there are 3 basic solution directions, each with a few options:

- Increase resources
  - Hire more workers
  - Use subcontractor's labour
  - Work in overtime or an extra work shift
  - Break up activities in order to use a more diverse workforce; this reduces the bottleneck of the most demanded type of workforce
  - Use more productive staff
- Reduce scope
  - Subcontract part of the scope
  - Revise requirements
  - Defer part of the scope to later in the project
  - Check if there are any non-value adding activities to be deleted; activities that are not needed to meet the client's requirements
- Improve the process
  - Use process improvement
  - Change the logic between activities
  - Ask for expert assistance
  - Change strategy for performing the scope

Step 6: Communicate and focus on the baton tasks

The baton task is the first task that has to start on each chain that is protected by a project buffer. The ones involved in that task should fully prepare themselves and receive all input needed to start as soon as the predecessor is finished. This also improves focus and prioritisation for the project manager. The naming comes from the relay race analogy, where each next runner has to know that the runner before him is coming so he should be fully prepared and ready to start immediately once the baton is passed on (more in subsection 2.3.1).

Step 7: Compose a progress report

The progress report consists of:

- A table with for each buffer:
  - Buffer name (buffered endpoint)
  - Current colour zone (green, yellow or red)
  - Buffer used [%]
  - Chain complete [%]
  - The relative buffer consumption index (RBCI)
  - Buffer left [days]
  - Chain left [days]
  - Original buffer [days]
  - Original chain [days]
  - Baton task

- A fever chart for each project buffer showing the current colour zone, status history and variability profile.
- In case of multiple buffers (i.e. endpoints) or multiple projects, a fever chart showing the current positions in an overall fever chart. This prioritises the buffers (i.e. chains) and provides focus.
- Top three most crucial tasks and top three most critical risks in the upcoming two weeks.
- A date based chart showing the course of RBCI, buffer used and chain complete, with a data table underneath showing those 3 elements for all progress reports until now.

An example progress report of the RCCPM tool can be found in appendices 8 and 10.

4. Application of the Tool to Case Studies

This chapter discusses the application of the RCCPM tool to two different case studies of Damen Verolme Rotterdam. Afterwards a detailed example is given regarding the changes in schedule from traditional to RCCPM. Section 8 describes a sensitivity analysis of the tool, while section 9 is dedicated to showing the fever chart behaviour with various scenarios. Section 10 deals with the (extra) data the tool needs to start working with RCCPM and to improve its future use. A qualitative validation of the progress reports is described in section 11, followed by a discussion in section 12.

CASE 1: FABRICATING SPECIAL OFFSHORE EQUIPMENT

The first case study covers the fabrication of special offshore equipment for a pipe laying vessel. First a description of the case will be given in section 1. Section 2 covers the application of the RCCPM tool during the planning phase, while section 3 focuses on progress reporting. The general approach of the application of the RCCPM tool is the same as for the second case.

4.1 Case Description

In contrast to the second case, this case is not a tender; the project has been executed at the yard during the summer of 2016. It encompasses the fabrication of special equipment for an offshore contractor's vessel. The equipment is made of steel and is subject to extensive quality control, with only small tolerances allowed. Before the actual fabrication starts, there is material to be procured by the yard and documents to be approved by the contractor. The fabrication is mostly done in a covered shop. The project is finished when all equipment is finished and ready for transport at the quayside.

4.2 Application of the Tool in the Planning Phase

This section shows the step-by-step application of the RCCPM tool to the case during the planning phase according to section 3.7. A combination of the traditional and RCCPM schedule can be found in appendix 6.

Step 1: MS Project XML 2013 export

The traditional baseline schedule, made in Primavera, is exported to be used by MS Project.

Step 2: Import the Primavera XML export

The exported file of step 1 is imported by MS Project and can now be used for the next step.

Step 3: Prepare the schedule to be used by RiskyProject and ProChain

This subsection describes the first changes to the schedule.

Eliminate Milestones

The traditional schedule contains 16 milestones in total. This project does not have any internal milestones; all milestones are originating from the contract between the shipyard and the client. All those milestones should be deleted, but currently they cannot be removed due to the type of contract.

Tasks without successors

The traditional schedule contains 22 tasks without successors. RCCPM cannot work with this, as it will regard this as a project with 22 endpoints and thus 22 buffers. The task relations are adapted in order to have buffers only for the final deliverables. There are four deliveries that all come together in the final task “ready for transport at quay”. A buffer will only be placed after this task.

Late Start

All tasks are scheduled to start as late as possible, except for milestones. In the traditional schedule, half of the tasks had to start as soon as possible. The other half were constrained to start or finish no earlier than a specified date; this is not necessary provided that all logic links are in place and prevent a project from moving as fast as possible.

Step 4: Import the MS project schedule or use the RiskyProject add-in

The MS Project schedule of last step is imported by RiskyProject and can now be used for the next steps.

Step 5: Define uncertainties for each activity

All 132 activity durations in the schedule are estimates and thus subject to uncertainty (i.e. common cause variation). Compared to case 2 this project is more a one-of-a-kind, different from what the yard normally does. Therefore, the uncertainties are slightly bigger:

- Activities follow a beta distribution with $\alpha = 2$ and $\beta = 4$.
- Each activity has a standard uncertainty of 85 and 130% of the base duration.
- The durations from the traditional schedule are the high estimates, if this number is indexed at 1.00; we can define the base duration as 0.77 and the low duration as 0.65.

The probability density function is plotted in Figure 21.

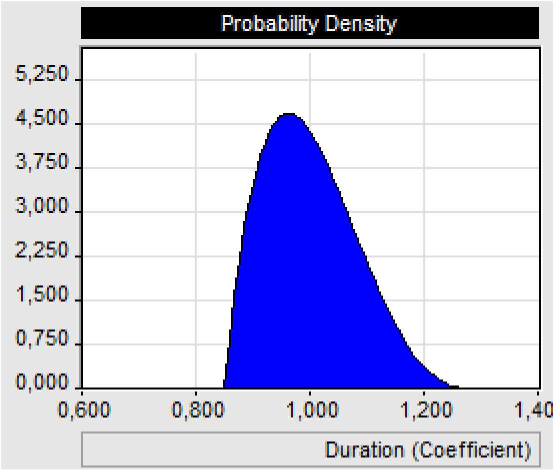

Figure 21: Probability density function

The numbers in this section are estimates and the influence of those estimates will be assessed by a sensitivity analysis in section 4.8.

Step 6&7: Define risks & opportunities and their effects and assign to activities

This step defines the most important risks and opportunities that have an effect on the project duration. In contrast to the second case, weather conditions are not influencing this project, as all work is performed in a shop. As the fabrication part of the project is performed during the summer period, the unavailability of qualified personnel is a major risk (see Table 8).

Table 8: Risks and opportunities

#	Risk name	Risk or Opportunity	Assigned to task(s)	Probability	Relative delay
1	Document not approved	Risk	All approvals	5%	10%
2	Early approval	Opportunity	All approvals	10%	-10%
3	Early delivery	Opportunity	All deliveries	20%	-10%
4	Late delivery	Risk	All deliveries	10%	10%
5	Test failed	Risk	All tests	5%	30%
6	Scarce machinery failure	Risk	All fabrication tasks	10%	5%
7	Lost-time injury	Risk	All fabrication tasks	1%	15%
8	Unavailability of qualified personnel during the summer	Risk	All fabrication tasks	10%	20%

Step 8: Perform the Monte Carlo simulation

Monte Carlo simulations are performed according to step 8 of the RCCPM planning tool in order to determine the focus (mean) duration of each activity. The risks, uncertainties and opportunities are based on those identified in steps 5, 6 and 7.

Step 9: Review the simulation results

The simulation results are reviewed and are considered reliable, 50000 round of simulation have been performed. The mean durations can be used in step 12.

Step 10: Open the MS Project schedule in ProChain

The MS Project schedule is opened again by using the ProChain add-in.

Step 11: Prioritise the endpoints

This step is not applicable to this project as there is only one endpoint.

Step 12: Fill in the focus and low-risk durations

The focus durations are the mean durations of the performed MC simulation of step 8. The low-risk durations are those durations that were in the traditional schedule. Both focus and low-risk durations for each activity can be found in appendix 6.

Step 13: Calculate and place the buffer(s)

The project buffer is calculated by the standard SSQ method, following section 3.6.2. A total project buffer of 17 days is needed to offer the same level of protection against risks and uncertainties as the traditional schedule. The buffer ends at the last possible delivery day and all other activities are pushed back as far as possible; resulting in a schedule that is 7 days shorter than traditional (i.e. the project can start 7 days later). Both procurement and fabrication engineering could be seen as the start of the project, with RCCPM both activity packages start 7 days later than with traditional PM. If we assume that half of the project buffer will be used, then the project needs 15.5 days (10%) less in total compared to the traditional PM method. The total lead-time reduction is visualized in Figure 22.

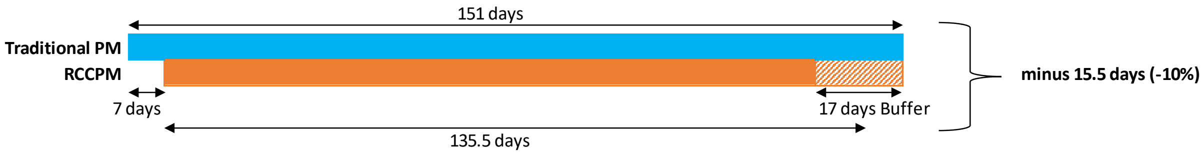

Figure 22: Lead-time reduction

4.3 Progress Reporting

The last traditional progress report of this case can be found in appendix 7. There is also a RCCPM progress report of the same status date in appendix 8, made by following the steps of section 3.8. The actual progress has been translated as close as possible to how it would look like with RCCPM. However, it cannot be said that the RCCPM report is 100% correct, as the only documented type of progress is the % complete while RCCPM uses the estimated amount of remaining days. The total progress at the status date is less with RCCPM, because activities start later than with traditional PM.

CASE 2: SERIAL PRODUCING OFFSHORE WIND TURBINE FOUNDATIONS

The second case study covers the fabrication of offshore wind turbine foundations. First, a description of the case will be given followed by the application of the tool during the planning phase in section 5. Section 6 focuses on progress reporting.

4.4 Case Description

The case is based on a tender proposal for the supply of offshore wind turbine foundations for an offshore wind park in the North Sea. The original tender and its schedule have been slightly adjusted in order to simplify its use. The case is also a tender project, so it has not yet been executed.

This research will contribute to a bigger plan of setting up a supply chain for the serial production of jacket type offshore wind turbine foundations (OWTF's) for deeper waters. For this case the engineering is already done be the client, but there is also engineering knowledge available at Damen Verolme Rotterdam. The scope of work for DVR is the fabrication of the jackets. Fabrication will primarily be done in open air at a partner shipyard in Asia. Afterwards subassemblies (2 parts) will be shipped to DVR for completion. The fact that DVR also deals with the design, leaves the option open to adjust the design if this proves to deliver lower production times and/or costs. In total 72 jackets will be fabricated in six batches of twelve jackets each. Each batch is transported by a semi-submersible heavy load vessel. Three of such vessels are arranged, each one providing two round trips.

One of the research themes of DVR for offshore wind is the development of a toolbox to control the serial production process; this is where this research fits in. Properly planned and controlled serial production of offshore wind foundations will contribute to lower the levelised cost of energy (LCOE) for offshore wind. Thus making offshore wind energy more attractive, speeding up the process of a more sustainable (energy) future.

4.5 Application of the Tool in the Planning Phase

This section shows the step-by-step application of the RCCPM tool to the case during the planning phase according to section 3.7. A combination of the traditional and RCCPM schedule can be found in appendix 9.

Step 1: MS Project XML 2013 export

The traditional baseline schedule, made in Primavera, is exported to be used by MS Project.

Step 2: Import the Primavera XML export

The exported file of step 1 is imported by MS Project and can now be used for the next step.

Step 3: Prepare the schedule to be used by RiskyProject and ProChain

This subsection describes the first changes to the schedule according to step 3 of the RCCPM planning tool.

Integrating the Schedules

The traditional schedule is made by integrating three existing tender schedules into one complete overall schedule (see appendix 9). The activities of assembling the jackets at DVR ("Assembly Jacket x.x") are not further specified in the schedule, because it would increase the amount of lines from 213 to 1021 and generally, those activities would only take about one day, which would not have been in line with the planning level used throughout the other parts of the schedule.

Eliminate Milestones

The traditional schedule contained 24 milestones in total. RCCPM aims to have the least amount of milestones as possible, ideally no milestones at all. RCCPM believes that having too much milestones will make the project take longer the strictly necessary. Milestones in the schedule encourage date driven behaviour. Perhaps an activity could start earlier, but because of the milestone, people are not prepared yet. Alternatively, an activity could have finished earlier if there would have been no milestone present, but because of the milestone, people will generally use all time available.

Milestones that should be deleted, but that currently cannot be removed are:

- Contract award; DVR has to adhere to this milestone, because it is put into the contract by the client.
- Start & end delivery FOB DVR; same reason as above.
- Issue drawings by the client; same reason as above.
- Load out of each batch at Asian yard and arrival at DVR; contract dates of shipping company.

All milestones stated above have to do with the current method of contracting. In this case, only between the client and the contractor (DVR) and between the contractor and the shipping company, but on a lower level this will also be the case for the contractor and the co-makers (subcontractors). An alternative method of contracting (based on game theory) is proposed in the recommendations (see section 5.3) that could solve this and other issues for implementing RCCPM in the maritime industry, an industry that is known to have many co-makers.

All milestones that are not directly part of the contract are deleted to eliminate date driven behaviour and encourage a relay race approach. Milestones to delete are:

- Steel order placed; order the steel as late as possible in order to avoid unnecessary wastes such as storage, transportation and defects.
- Strike steel; you should start when ready (relay race approach).
- Start construction of each batch; same reason as above.

Delete Floats

All floats that are part of the traditional schedule are deleted. A float protects the project locally, while RCCPM protects the project on a global level. Floats are also unwanted with a late start based schedule. The following floats are deleted:

- Floats before the three vessels are needed (18 days each)
- Floats before and after the load out at DVR (69 and 23 days)

Late Start

All activities are adjusted from an early start into a late start, except for milestones that are in the contract between the client and the contractor; which have a must start/finish on constraint.

Streamlining the Schedule

After making the changes above, the schedule was perfectly minimizing the duration of the three hired vessels. However, this caused a parallel execution of the construction of batch 3 and 4; and batches 4, 5 and 6 had to wait for almost a month after arrival at DVR before the assembly could start. Therefore, a free float of 18 days has been inserted for each of the three vessels in-between the two trips. This ensured that the construction of batch 3 does not run simultaneously with batch 4; and assembly can directly start once batch 4, 5 or 6 arrives at the shipyard. The lead-time did not change with this adjustment. Alternatively, one could also decide to hire 6 vessels that provide only 1 trip each, although this is a more expensive option.

Step 4: Import the MS project schedule or use the RiskyProject add-in

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The MS Project schedule of last step is imported by RiskyProject and can now be used for the next steps.

Step 5: Define uncertainties for each activity

All 110 activity durations in the schedule are estimates and thus subject to uncertainty (i.e. common cause variation). The partner shipyard is quite familiar with the fabrication process of similar structures (i.e. jack-up legs). For this research, some assumptions are made in order to carry out the analysis:

- Activities follow a beta distribution with $\alpha = 2$ and $\beta = 4$.
- Each activity has a standard uncertainty of 90 and 120% of the base duration.
- The durations from the traditional schedule are the high estimates, if this number is indexed at 1.00; we can define the base duration as $0.8\overline{3}$ and the low duration as 0.75.

Such a probability density looks as following (see Figure 23). This figure is from the activity "Sailing to DVR via COGH", but the shape is exactly the same for each activity.

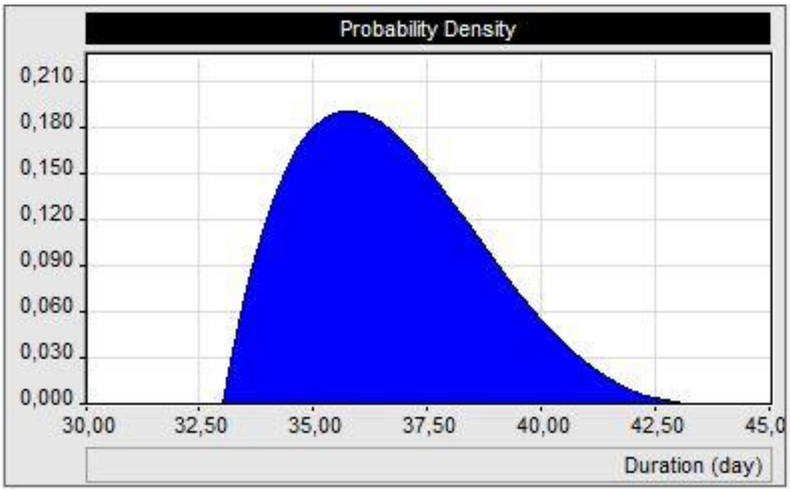


Figure 23: Probability density

The numbers in this section are estimates and the influence of those estimates will be assessed by a sensitivity analysis in section 4.8.

Step 6&7: Define risks & opportunities and their effects and assign to activities

The author's knowledge has been applied to brainstorm about those risks and opportunities (i.e. special cause variation) that have a substantial effect on an activity's duration (Table 9). The special cause variation comes on top of the common cause variation of the uncertainties. There are no long lead items and there is no E&I work, the only important delivery is steel. Fabrication will be done mostly in open air; therefore, weather can have an influence. Black swan events (a surprising event with a major effect) (Taleb, 2007) include a blockage of the Suez Canal (detour via COGH possible) and an attack of pirates. Unavailability of major equipment are the vessels, sheerlegs and crawler cranes; it is assumed that there are enough alternatives, but time is lost to find and get the equipment at the correct location.

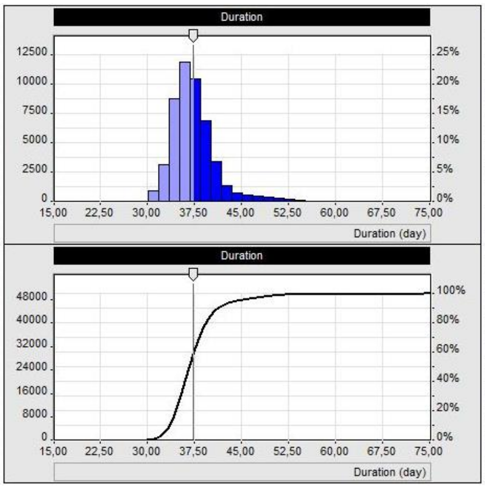
Table 9: Risks and opportunities

#	Risk name	Risk or Opportunity	Assigned to task(s)	Probability	Relative delay
1	Late steel delivery	Risk	Steel delivery	10%	10%
2	Early steel delivery	Opportunity	Steel delivery	20%	-10%
3	Bad weather conditions	Risk	All construction, shipment and assembly tasks	20%	5%
				10 %	10%
4	Good weather conditions	Opportunity	All sailings and lifts	20%	-5%
				10%	-10%
5	Acceptance test failed	Risk	Acceptance testing	5%	30%
6	Scarce machinery failure	Risk	All construction and assembly tasks	10%	5%
7	Suez canal blocked	Risk	Sailing to Asia via Suez	1%	50%
8	Unavailability of major equipment	Risk	All sailings and lifts	5%	30%
9	Attack of pirates	Risk	All sailings	0.2%	50%
10	Lost-time injury	Risk	All construction and assembly tasks	1%	15%

Step 8: Perform the Monte Carlo simulation

Monte Carlo simulations are performed according to step 8 of the RCCPM planning tool in order to determine the focus (mean) duration of each activity. The simulation itself is performed on the whole project, where each single activity is influenced by the other activities and risks. The low-risk durations are those durations that were in the traditional schedule. The risks, uncertainties and opportunities are based on those identified in steps 5, 6 and 7. Both focus and low-risk durations for each activity can be found in appendix 9. Typical activity results of the MC simulation looks as Figure 24 (the same activity as Figure 23).

Num. of samples	50000
Minimum	29,8 days
Mean	37,26 days
Maximum	73,97 days
Range	44,17 days
P1/P99 range	19,76 days
P5/P95 range	11,48 days
P10/P90 range	7,63 days
P20/P80 range	4,81 days
P30/P70 range	2,98 days
Variance	107,77 days
Std.Deviation	3,67 days
Semi Std.Dev.	2,74 days
Skewness	1,644876
Kurtosis	4,932355



5th Percentile	32,64 days
10th Percentile	33,57 days
15th Percentile	34,1 days
20th Percentile	34,54 days
25th Percentile	34,94 days
30th Percentile	35,3 days
35th Percentile	35,65 days
40th Percentile	35,99 days
45th Percentile	36,34 days
50th Percentile	36,69 days
55th Percentile	37,05 days
60th Percentile	37,43 days
65th Percentile	37,84 days
70th Percentile	38,28 days
75th Percentile	38,76 days
80th Percentile	39,35 days
85th Percentile	40,1 days
90th Percentile	41,19 days
95th Percentile	44,11 days

Figure 24: Activity results of a MC simulation

Step 9: Review the simulation results

The simulation results are reviewed and are considered reliable, 50000 round of simulation have been performed. The mean durations can be used in step 12.

Step 10: Open the MS Project schedule in ProChain

The MS Project schedule is opened again by using the ProChain add-in.

Step 11: Prioritise the endpoints

This step is not applicable to this project as there is only one endpoint.

Step 12: Fill in the focus and low-risk durations

The focus durations are the mean durations of the performed MC simulation of step 8. The low-risk durations are those durations that were in the traditional schedule. Both focus and low-risk durations for each activity can be found in appendix 9.

Step 13: Calculate and place the buffer(s)

The project buffer is calculated by the standard SSQ method, following section 3.6.2. A total project buffer of 52 days is needed to offer the same level of protection against risks and uncertainties as the traditional schedule. The buffer ends at the last possible delivery day and all other activities are pushed back as far as possible; resulting in a schedule that is 28 days shorter than traditional (i.e. the project can start 28 days later). If we assume that half of the project buffer will be used, then the project needs 54 days (9%) less in total compared to the traditional PM method. The total lead-time reduction is visualized in Figure 25.

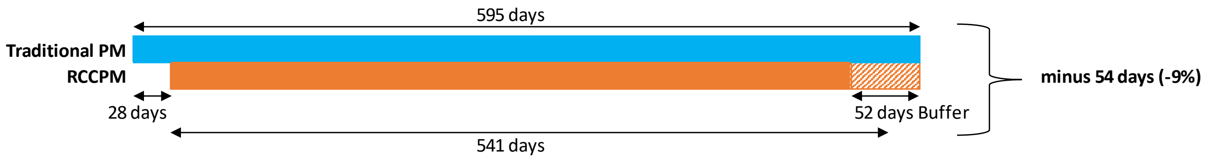


Figure 25: Lead-time reduction

4.6 Progress Reporting

This section shows how a typical RCCPM progress report would look like about halfway through the project. For this case, there is no extensive comparison between RCCPM and traditional progress reporting as the case is a tender project without a man-hour schedule and without actual progress. A typical RCCPM progress report for this case can be found in appendix 10 and is made following the steps of section 3.8 (a traditional progress report for case 1 is available in appendix 7). It shows the progress for the scenario that the project has started reasonably well, but in the last months critical activities have had serious delays leading to a red coloured position in the fever chart.

GENERAL APPLICATION OF THE RCCPM TOOL

4.7 Detailed Example of a Fictive Case

A fictive case has been made to show in a more detailed step-by-step approach the operation of the RCCPM tool. The project scenario consists of a semi-submersible drilling rig that has been cold stacked for years in the Mediterranean port of Valetta due to a low oil price. During those years no maintenance has been performed and the steel hull is severely corroded in the hot water. Recently, the offshore contractor has won a tender and has chosen to use the rig for the work. The scope of the yard consists of transport to the yard and renewal of both steel and equipment in order to make the rig fully operational again.

4.7.1 Schedule Changes

This subsection goes into more detail regarding the schedule changes by going through a small example step by step. A fictive network schedule has been made containing a variety of traditional scheduling pitfalls. The steps and changes are similar to those performed in cases 1 and 2. Appendix 11 shows seven schedules from traditional all the way to the final RCCPM schedule.

The project has 10 tasks (A to J) and should be delivered to the client on 9-1-18 according to the contract. The company has decided internally that task H (placing and installing new equipment) should start on 20-10-17 and to reach the milestone, a free float of 11 days has been inserted beforehand. The critical path (and later the critical chain) is shown in red. All non-critical tasks are scheduled to start as early as possible. This starting schedule corresponds to Figure 26.

ID	Task Name	Duration	Start	Finish	Predecessors
1	Task A: Transport to the yard and docking	13 days	Fri 23-6-17	Tue 11-7-17	
2	Task B: Inspection of equipment	27 days	Wed 12-7-17	Thu 17-8-17	1
3	Task C: Provide access to corroded hull	14 days	Wed 12-7-17	Mon 31-7-17	1
4	Task D: Removal of old steel	6 days	Tue 1-8-17	Tue 8-8-17	3
5	Task E: Removal of old equipment	34 days	Fri 18-8-17	Wed 4-10-17	2
6	Task F: Placing new steel	21 days	Wed 9-8-17	Wed 6-9-17	4
7	Task G: Checking if equipment is suitable for remanufacturing	7 days	Thu 5-10-17	Fri 13-10-17	5
8	<Free Float for start task H>	11 days	Thu 5-10-17	Thu 19-10-17	5
9	Milestone for Start of Task H	0 days	Fri 20-10-17	Fri 20-10-17	
10	Task H: Placing and installing new equipment	43 days	Fri 20-10-17	Tue 19-12-17	5;8;9
11	Task I: Painting scope (complete hull)	28 days	Thu 7-9-17	Mon 16-10-17	6
12	Task J: Testing and comissioning	14 days	Wed 20-12-17	Mon 8-1-18	10;11
13	Contract delivery to the client	0 days	Tue 9-1-18	Tue 9-1-18	12

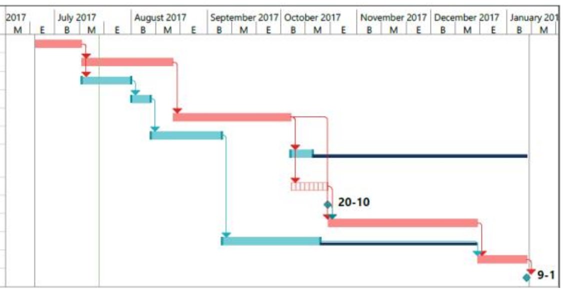


Figure 26: Starting schedule

The first change in the schedule is making sure there is only one endpoint as the project should only have one buffer. Therefore, task G is connected to the final task: task J. The second change is the removal of the internal milestone and the accompanying free float. This change causes the previous tasks to not be critical anymore. Therefore, change 3 pushes those tasks forward so they are critical again and there is no slack inside the critical path anymore.

The fourth change is adjusting all non-critical tasks to start as late as possible instead of as early as possible; the complete schedule is now free of slack. Afterwards, Monte Carlo simulations are performed with uncertainties, risks and opportunities as input. These simulations deliver the P50 duration of each task, the so-called focus duration. Change 5 involves filling in these focus durations, as opposed to the traditional low-risk durations, and pushing each task backward as far as possible; each task starts as late as possible. In order to protect the schedule at the same level of contingency as traditional, a project buffer is inserted at the end of the chain in change 6. The size of this buffer is calculated by the standard SSQ formula of subsection 3.6.2 and shown below;

$$\sqrt{(13-10)^2+(27-21)^2+(34-26)^2+(43-33)^2+(14-11)^2} = 15\text{ days}$$

4.7.2 Progress Reporting

This subsection shows a fictive progress scenario and its visualisation in a fever chart for the project at five points in the project; the 1st of September, October, November, December and January. The fever chart at the end of the project is visualised in Figure 27. A fever chart of the four earlier points in time can be found in appendix 11. Complete progress reports have already been sufficiently covered in case 1 and 2 (appendices 8 and 10).

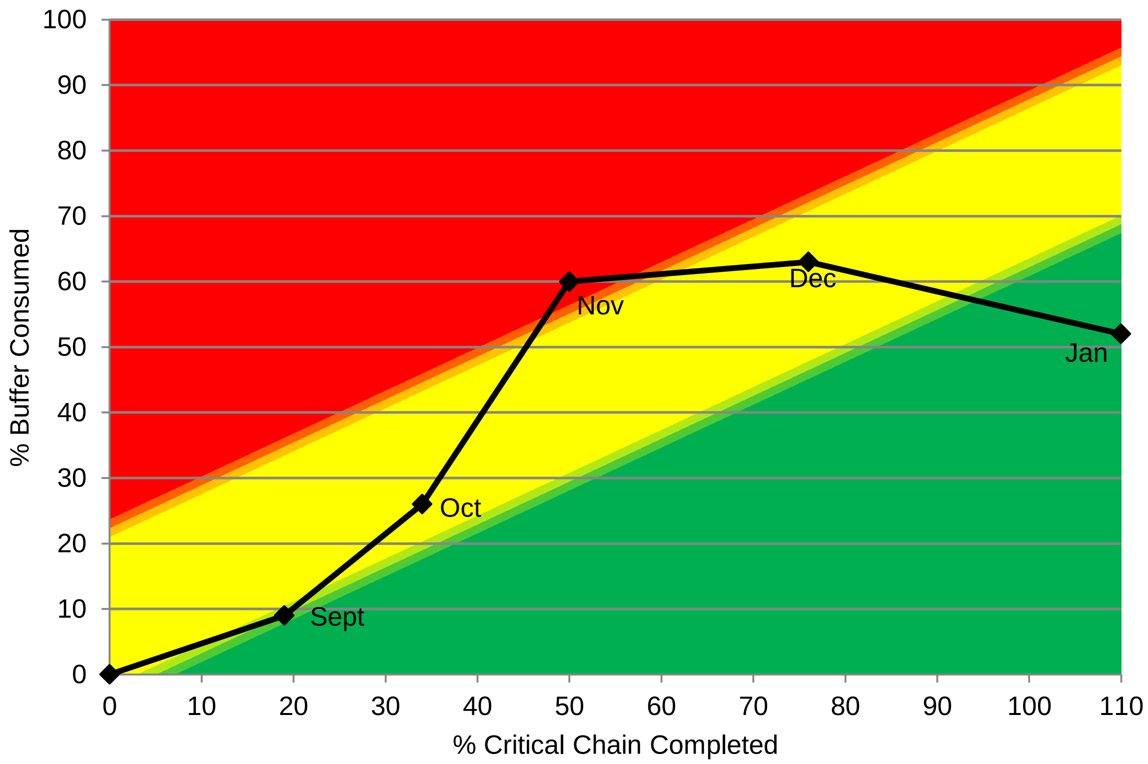


Figure 27: Fever chart at the end of the project

The project starts off quite well and on the 1st of September, a month after the start, the project is safely positioned in the green zone. However, during the month of September a VOR is issued by the client; before removing the old equipment, extra lights should be placed to allow working according to the client's safety standards. This VOR affects the work on the critical chain and an extension of the deadline is not possible as the rig has to be operational on time. This extra work without getting extra buffer causes the fever chart to end up in the yellow zone on the 1st of October. At this point the causes of the buffer use should be analysed and a mitigation plan should be made.

During the month of October things get worse and a major risk strikes the project; during the removal of old equipment a gas leak is detected an the yard has to be cleared. After a few days the source of the leak is found and closed. Fortunately, this risk has been identified during the risk assessment in the planning phase and the buffer size has been adjusted accordingly. This event is visible in the fever chart of the 1st of November and a steep line causes the project to end up in the red zone. A mitigation plan should now be executed. The plan is successful and on the 1st of December the project is back in yellow. The plan still works through in the remainder of the project and on the 1st of January the project is finished, on time and with a buffer use of about 50%.

4.8 Sensitivity Analysis

This section assesses the sensitivity of the outcomes of the RCCPM tool by varying the estimated range of uncertainty. Case 2 is used to perform this analysis and 50000 rounds of simulation have been carried out to achieve reliable results. It is important to know the influence of the uncertainty and risks estimates. The important outcomes to check are:

- The average change in activity duration
- The change in buffer size
- The change in the total lead-time of the project

First, the uncertainty range is varied by +/- 10% and +/- 20% as shown in Table 10. For case 2 a standard uncertainty range of 90 to 120% of the base duration was chosen, this range of 30% is varied.

Table 10: Outcomes of the sensitivity analysis

Change in uncertainty range of	New range of uncertainty	Causes an average change in activity (focus) duration of	Causes a change in buffer size of	Causes a change in the lead-time of
- 20%	92.3 - 115.4%	+ 4%	- 23%	+ 1.3%
- 10%	91.2 - 117.6%	+ 2%	- 11%	+ 0.7%
+ 10%	88.8 - 122.4%	- 2%	+ 11%	- 0.7%
+ 20%	87.5 - 125.0%	- 4%	+ 23%	- 1.3%

The results show that an increase in uncertainty leads to a decrease of the average activity duration, while the buffer size increases. This can be explained due to the fact that the difference between the focus and low-risk duration becomes bigger, meaning that there is more to cut in the duration estimate. If we cut more of the traditional low-risk duration, then the focus duration decreases. The buffer size is based on the sum of the cut-away parts, so it increases. Even though the buffer size increases by more than the average activity duration decreases, the lead-time still decreases, because the buffer determines only about

10% of the lead-time. The total effect of a change in the uncertainty range on the lead-time is only limited. A decrease of uncertainty works the exact opposite.

4.9 Fever Chart Dynamics

In this section, seven scenarios are presented in order to show the dynamics of the fever chart during a project. The base fever chart is used as a starting point for all scenarios. All fever charts can be found in appendix 12. The first six scenarios are chosen to show how the fever chart reacts to a VOR (variation order request). A VOR can mean either more or less work and for the fever chart it is necessary to know whether this VOR is on the critical chain or not and if the deadline is extended, advanced or not changed. The seventh scenario shows what happens in case of a risk. The fever charts have been adapted according to step 2 of the RCCPM tool in the execution phase (section 3.8).

The seven scenarios are:

1. VOR/more work, the VOR is on the critical chain and the deadline is extended.
2. VOR/more work, the VOR is on the critical chain and the deadline is not extended.
3. VOR/more work, the VOR is not on the critical chain and the deadline is not extended (with extension of the deadline is less likely to happen, but the chart would look the same).
4. VOR/less work, the VOR is on the critical chain and the deadline is advanced.
5. VOR/less work, the VOR is on the critical chain and the deadline is not advanced.
6. VOR/less work, the VOR is not on the critical chain and the deadline is not advanced (with advancing the deadline is less likely to happen, but the chart would look the same).
7. A risk that strikes, such as an important delivery (e.g. thrusters of a semi-submersible heavy lift vessel, that are getting serviced by a third party located away from the yard) that is delayed and that has an effect on an activity on the critical chain.

When looking at the fever charts you will see that at a first glance they all look quite similar. Please note that the fever charts of scenarios 3 and 6 are 100% identical to the base scenario, because they do not affect the critical chain. The historical data points in the fever chart remain in the same position, no matter what happens to the project. This is a significant benefit compared to the traditional earned value chart, where lines and historical data points often change position after such scenarios.

In most cases one can simply lengthen or shorten the size of one or both the axes of the fever chart. The horizontal axis gets lengthened if work is added on the critical chain and shortened if work is removed from the critical chain. Work that is added or removed and that was not part of the critical chain has no influence on the fever chart. The vertical axis gets lengthened or shortened if the deadline of the project is extended or advanced. Scenario 7 shows a risk that causes a standstill of the work on the critical chain and therefore the line is vertical; this is the extreme case, the line would be more horizontal if there is still work on the critical chain that can continue or if the fever chart is updated after the added duration of the risk has passed.

Scenarios variability profile

On the last page of appendix 12, four more fever charts are placed which differ in the course of the variability profile (the grey dashed line in the fever chart). Four different basic scenarios are presented and for each one an example is given.

1. There is equal variability throughout the whole project. This happens if all risks are equally spread throughout the time of the project and each phase has equal complexity.
2. The majority of the variability is located at the start of the project. This could be the case if the complete scope of the project is not clear upfront and inspections are needed to determine how much work needs to be done.
3. The majority of the variability is located at the end of the project. This typically happens if there is a complex object that undergoes extensive testing or installations that need to be commissioned. In case of a failed test, durations could increase significantly.
4. The majority of the variability is located in the middle of the project. This is the case if risks mainly influence the tasks that can be found at the heart of the project.

4.10 Data for Implementation and Improvement of RCCPM

This section covers what data is needed for the implementation of RCCPM in subsection 4.10.1. Subsection 4.10.2 shows how data that is generated by the RCCPM tool can be used for continuous improvement of the tool.

4.10.1 Data for Implementation of RCCPM

The CCPM part of RCCPM does not require much extra data or steps compared to traditional PM. In fact it does not require any extra data; one should only change the question when asking for the progress of activities. RCCPM works with the estimated amount of remaining days of each activity instead of the estimated % of (physical) completion, the progress sheets should be changed accordingly. It does however requires training to teach about the differences in traditional PM and RCCPM and mostly the changes in people's behaviour. A lead implementer would be needed with knowledge about traditional PM, RCCPM and change management. It is also important to note that for implementing RCCPM basic knowledge about project management, risk management and process improvement should be available throughout the organisation.

The risk part of RCCPM requires extra data to make the shift from a deterministic to a probabilistic schedule. Monte Carlo simulations are used to determine the P50 (focus) duration of each activity. To perform the MC simulations you need to estimate the standard (common cause) uncertainty for the project. Secondly, the risks and opportunities in the project together with their probability, effect (relative delay) and a list of the activities and resources they affect should be identified. This risk part means extra work for the project planner, who is best able to assess the impacts on the project duration. A brainstorming session about the risks and opportunities should be organized with a bigger and more versatile group of people in order to limit possible biases.

At the start of implementing RCCPM it is recommended to make a general risk register consisting of all relevant risks that can affect projects' duration in the organisation. Once that is in place it can be used as a template for all projects by simply checking a box if that risk is applicable to the project. At the start, quantifying the uncertainties and the probability and impact of risks and opportunities will be estimates based on expert judgement.

During each project, data can be registered to help in quantifying the uncertainties and the probability and impact of risks and opportunities. For uncertainties this means a registration of the planned and actual duration of each activity, which is already done by default at DVR. The difference between these two durations can be plotted in a figure (see Figure 28) and can be utilised to adjust the uncertainty estimates.

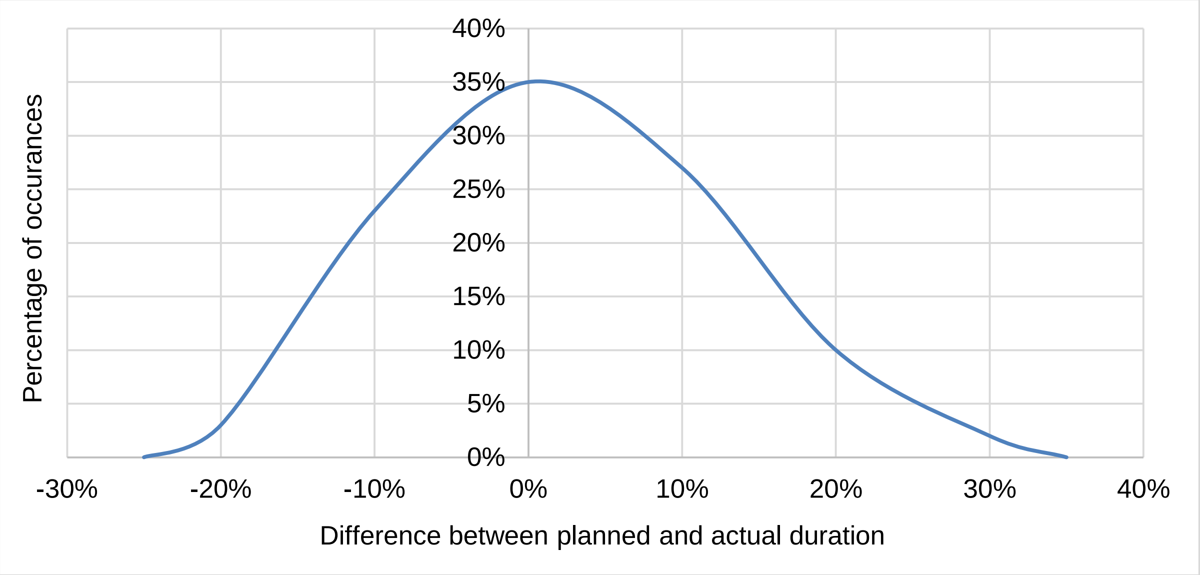


Figure 28: Example of empirical data for determining uncertainty

The estimates of risks and opportunities can be adjusted and improved by using the risk register that should be made as part of implementing RCCPM. During the project it should be registered if a risk or opportunity occurs; this can be a tick in the box of the risk register. This helps to better estimate the probability. If there is a risk or opportunity that was not yet part of the register, then it should be added to it. The project manager should, as part of the lessons learned report, write about the impact of the risks and opportunities that occurred during the project. This can be utilised to fine-tune the effects (relative delay) of risks and opportunities.

To compose the RCCPM progress reports some more sets of data are needed, but they do not require any extra effort as they are an output of the tool in an earlier stage. The buffer status (colour zone, % buffer used and % chain complete) and baton task are given as soon as the progress is updated. The crucial tasks and critical risks are resulting from the MC simulations.

4.10.2 Data for Improvement of RCCPM

RCCPM and specifically the parameters of the fever chart can also be used in a combination with six sigma techniques. RCCPM already focuses on assessing and managing the variation, with six sigma tools this variation could be reduced as part of a project quality management system. As an example, you could make a Pareto chart to identify the biggest contributors to buffer consumption. Other options are a process behaviour chart of the %

buffer used at the end of a series of projects, which can be used to optimize the buffer sizing (see Figure 29; for this example the action would be to cut the buffers in size by 20%). One could make a similar graph for the point in the projects when they reach 25%, 50% and 75% of the buffer used in order to improve the intercepts and slopes of the green, yellow and red areas in the fever chart.

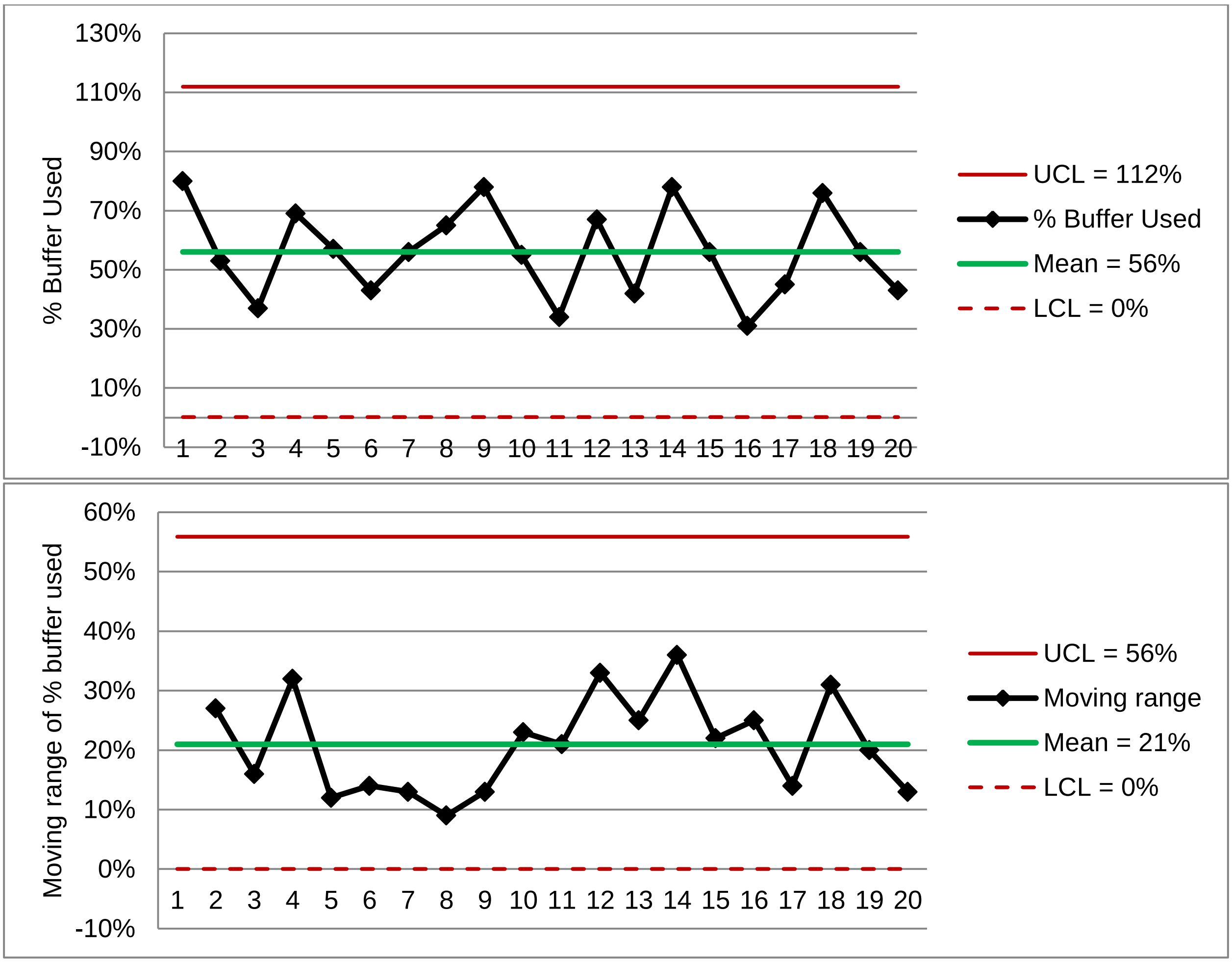


Figure 29: Process behaviour chart of the % buffer used

4.11 Qualitative Validation of the Progress Reports

The progress reports are validated by a questionnaire amongst 18 people (16 students and 2 employees) at Delft University of Technology during the course "Delft Systems and Simulation Approach" on the 10th of May 2017. This is an elective course of the master in marine technology for those who are interested in ship production and shipyard strategies. All participants had at least basic knowledge about project management. This validation is done to get an objective idea of how the progress visualisations are valued amongst the public.

Beforehand, a small presentation of 10-15 minutes has been given that covered the elements of the progress reports. This has been done as factual as possible in order not to influence the results of the questionnaire. Because of the same reason the progress reports were called "Type A" and "Type B" instead of traditional (A) and RCCPM (B); some students might prefer traditional approaches in general, while others have a natural tendency to move away from traditional approaches. It has to be noted however that the class was already familiar with earned value as this has been a topic during the course, while RCCPM was completely new. The complete questionnaire can be found in appendix 13. The progress reports used for this questionnaire are in appendix 7 (type A) and appendix 10 (type B).

Questions 3 and 4 were designed to get an idea about the participants' opinion on concepts behind RCCPM. During the presentation, no attention has been given to this. It confirms the idea that eliminating multitasking and starting each task as late as possible is indeed counterintuitive to many people. Clearly, for a full implementation of RRCPM attention should go to the understanding of these and underlying concepts, such as student syndrome and Parkinson's Law. At question 4, 39% opted for "makes no difference" which can be true, but only for tasks on the critical chain; they have zero slack.

Q3: To reduce the lead time (duration) of a project you should:	
Encourage multitasking	56 %
Eliminate multitasking	28 %
Makes no difference	17 %

Q4: To reduce the lead time (duration) of a project you should:	
Start each task as early as possible	56 %
Start each task as late as possible	6 %
Makes no difference	39 %

Question 5 has been designed to let the participants have a first acquaintance with all the elements of the two progress reports. Ranking the elements in the order of usefulness forces to have a critical look at all of them. Aggregating all answers gives the ranking below:

1. Earned value chart
2. Fever chart
3. 3 most crucial tasks
4. Histogram
5. Date based chart
6. Baton task
7. 3 most critical risks

Q5: Please rank the (7) elements of the progress reports in the order of usefulness	Average rank	Rank 1	In Top 3	Rank 6+7 & not useful
Earned value chart	1.9	56 %	89 %	6 %
Histogram	3.9	11 %	39 %	28 %
Baton task	5.0	-	17 %	39 %
Fever chart	2.8	22 %	67 %	-
3 most crucial tasks	3.7	11 %	39 %	28 %
3 most critical risks	5.4	-	17 %	61 %
Date based chart	4.9	-	33 %	39 %

The earned value chart is still favourite for the majority. Somewhat surprising is the difference in ranking between the crucial tasks and the critical risks, which both come from MC simulation and both show those 3 tasks/risks that can most influence the delivery date. Looking at the comments, this stems from the fact that all tasks are sure to be executed, while most risks will probably not happen. Even though the element of the 3 most critical risks was ranked lowest, only 2 participants found it not useful, so the big majority does see benefit in it.

Questions 6 to 9 are more specific, closed questions on important points for the progress reports. Questions 7 and 8 show that the earned value chart is better understood than the fever chart. This is not a big surprise, as the students have already worked with earned value. This again shows that an implementation of RCCPM requires extensive training, even more because of the fact that earned value is seen as the standard and "best practice" for controlling projects. Participants already largely agreed however that the fever chart's three-colour system is superior in knowing when to perform control actions compared to the EV chart.

Participants also largely agreed that an estimation of the amount of days an activity still needs (used for the fever and date based chart) is preferred over the estimated % of completion (used for the EV chart and histogram). Comments included "I want to see if I respect my deadline." and "Days are measurable, the % doesn't tell you how long you still have to go." The best comment maybe is "using % completion data for decisions is equivalent to driving your car by looking through the rear view mirror". Concluding you could say that the participants prefer forward looking information to information that is already history as soon as you receive it.

Participants also commented that they would like to receive both if possible; this is possible, but one could then ask which one you use for monitoring and controlling. In case it is always the same, you do not need the other. One could also choose to use the one that provides either the best or the worst view on the project. At the end, you collect the data to make a progress chart, which can be either earned value, or fever chart, or in this case both charts. You can show both charts and for instance use the EV chart for monitoring cost performance and the fever chart for monitoring time performance, although cost performance could also be monitored by a fever chart. This cost fever chart is described in section 4.11.

Q6: What piece of information would you prefer when making a decision as a project manager:

The estimated % of (physical) completion of each activity (like 40% complete)	17 %
The estimated number of days needed to complete each activity (like 10 days remaining)	78 %
No preference	6 %

Q7&8: Do you understand how to interpret …	an earned value chart?	a fever chart?
Yes, completely	78 %	44 %
Yes, but not completely	22 %	56 %
No	-	-

Q9: The three coloured (traffic light) system of the fever chart provides better info on when to perform control (mitigation) actions compared to the earned value chart.

True	82 %
False	18 %

The last two questions were designed to let the participants decide which progress report they prefer. Question 10 first forces to think about the criteria that are important for a progress report, rank them, and assess the two types on those criteria. It shows that the most important criterion is 'the best information to make a decision for the upcoming week of the project'; RCCPM wins this one by 17 percentage points. On the other hand, the second most important criterion 'clarity about the status' is won by traditional with 17 percentage points. This, together with the criterion 'quickest overview' can be explained by the fact that the students were already familiar with EV. RCCPM is clearly preferred for the criteria 'clearest priorities' and 'most helpful to get the project back on track'. The criteria 'most information' and 'best focus' are thought to be not very important for a progress report. All scores are visualised in the bubble chart below, with the size of the bubble depending on the average rank (see Figure 30).

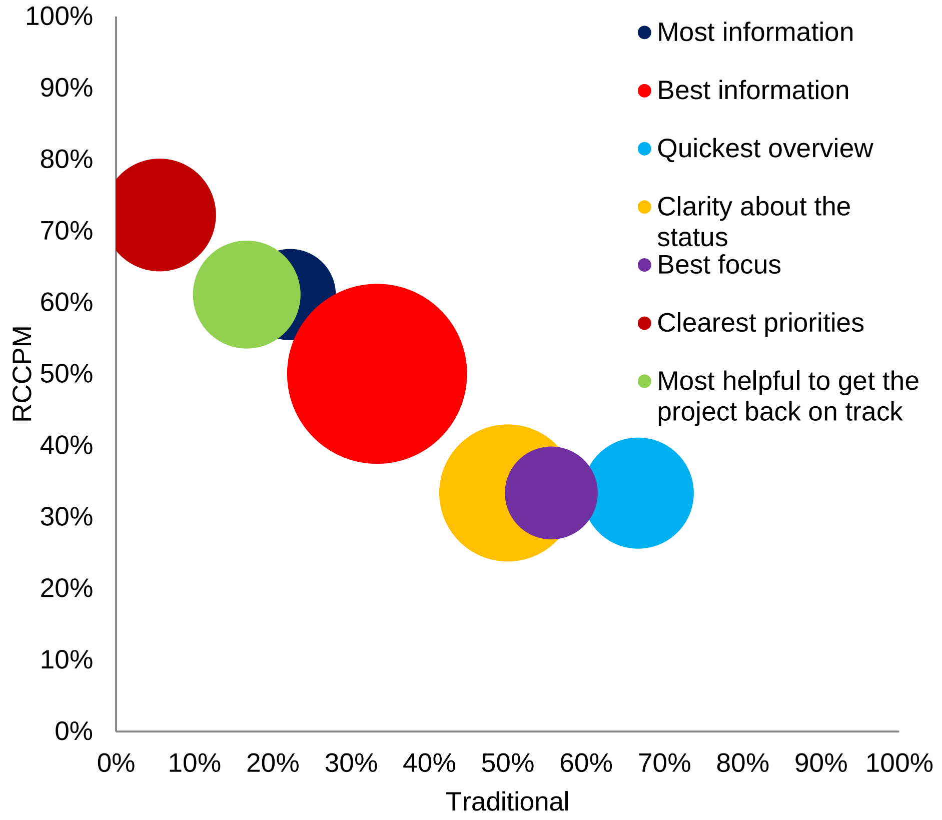


Figure 30: Assessment of the progress reports

Q10: Please assess the 2 progress reports on the list of criteria below.	Traditional	RCCPM	Equal	Average rank
… gives you the most information to make a decision for the upcoming week of the project?	22 %	61 %	17 %	5.8
… gives you the best information to make a decision for the upcoming week of the project?	33 %	50 %	17 %	1.5
… gives you the quickest overview/takes the least time to understand?	67 %	33 %	-	3.9
… provides more clarity about the status of the project?	50 %	33 %	17 %	2.6
… provides you the best focus?	56 %	33 %	11 %	5.6
… provides you the clearest priorities?	6 %	72 %	22 %	3.8
… would be the most helpful to get the project back on track?	17 %	61 %	22 %	4.2

Question 10 is also designed to let the participants systematically think about their preference for a progress report before answering question 11. Based on the ranking of each criterion and the scores for traditional, RCCPM and equal, one could predict how question 11 will be answered; 6 participants for traditional, 9 for RCCPM and 3 with no preference. However, the actual score is 9 for traditional, 7 for RCCPM and 2 with no preference. Based on the comments of question 11, this difference can be explained due to the fact that all participants were already familiar with the traditional progress report and when they have to choose some people prefer the well-known option.

Q11: Next week you will receive only 1 progress report. You're the project manager, so you can decide which one it will be. Do you have a preference?	Answer to Q11	If based on Q10
Yes, Traditional	50 %	33 %
Yes, RCCPM	39 %	50 %
No preference	11 %	17 %

The participants were asked to explain their choice in question 11; those comments are placed in appendix 14.

4.12 Discussing a Cost Buffer Fever Chart and the "S" in Earned Value

When going through the comments of the questionnaire and given the fact that EV is familiar to many people; the question rises whether or not a figure can be made that has elements of both EV and the fever chart.

Some people prefer EV, because it can also be used to manage the cost of a project. This is also possible with RCCPM and is very similar to the schedule buffer. One could make probabilistic cost estimation and use the P50 as the base, with the difference between P50 and the traditional level of cost estimation going to a cost buffer. During the project, you can keep track of the cost and check the difference between the actual cost and the P50. If you use more than the P50 estimate, you will use some of your buffer, which again can be shown in a fever chart. You will then have 2 fever charts; one for time and one for cost. For the cost buffer fever chart, the horizontal axis will be called % baseline budget consumed and can be calculated with:

$$\frac{EV}{BAC - Cost\ Buffer} * 100\%$$

The vertical axis will be called % cost buffer used and can be calculated with:

$$\frac{CV}{Cost\ Buffer} * 100\%$$

The solution in last paragraph provides a method that uses both progress concepts and that can manage both time and cost. The earned value chart is said to show both schedule and cost performance. However, what is called schedule in EV terminology actually has no direct relation with the time or delivery date of the project; it only shows how much of the work scope is finished and how much work is still needed. It would therefore be more suited to replace schedule for scope in the SV and SPI figures. In addition, it does not discriminate between critical and non-critical work, so the EV chart could look very good without having much progress on the critical tasks. Furthermore, the measure is amount of work, which means that a task with many hours to work on has more influence on the chart then a task with less hours of work. However, the task with less work might have a bigger duration because less people can work on it simultaneously then the task with more work.

5. Discussion of the Results, Conclusions and Recommendations

This last chapter discusses the lead-time reduction results of the case studies in section 5.1. A discussion of the progress reports has been included directly with the setup and results of the questionnaire in sections 4.11 and 4.12. Subsequently conclusions are made by answering the main and sub research questions in section 5.2. Finally, recommendations for further implementation and improvement of RCCPM are described in section 5.3.

5.1 Discussion of Lead Time Reduction

As seen in last chapter, case study 1 has shown an estimated lead-time reduction of 10%, while case study 2 reached 9%. This is substantially less than the average reduction of 40% that CCPM consultancy and software companies claim (as shown in subsection 2.11.1). There are a variety of explanations for this difference:

- The possible gains from eliminating multitasking, the student syndrome, Parkinson's Law and comparable psychological effects during project execution are hard to quantify and are therefore not part of the 9-10% lead-time reduction. It is to be expected that a real-life case study shows a bigger lead-time reduction.
- The results are quite dependent on the assumptions about uncertainty. If we assume more uncertainty in our estimations than the lead-time reduction will be bigger as well.
- The 9% reduction in case 2 is compared to the traditional schedule. This traditional schedule already contained buffers to protect the project against risks and uncertainties, such as a 23-day buffer at the end (where you can find a 52-day project buffer now). The reduction would have been bigger if there were no buffers in the traditional schedule.
- Those companies that have said to achieve 40% lead-time reduction, cut their durations in half (the focus duration is only 50% of the low-risk duration). This seems to be impossible in the maritime industry, because activities have a technical minimum required duration that is constrained by for instance the speed of a ship, the amount of machine operations or the amount of people that can (safely) work in an area. For these cases, the average difference between focus and low-risk durations is 15-20% instead of 50%.
- Literature assumes projects to be scheduled at P95 or P90. In the maritime industry, this number is substantially lower, probably about P75. A lower confidence level means that there is less to "win" by scheduling at P50.
- The 40% lead-time reduction number comes from publicly shared experiences by CCPM consultancy and software companies; this number is probably highly biased as only the best experiences are openly shared in order to sell their services.

- These cases and the maritime industry in general works with many co-makers (subcontractors), if they keep working according to their traditional PM paradigm than the reduction cannot reach its global optimum. An alternative method of contracting can help and is recommended in section 5.3.

5.2 Conclusions

In this section, each of the sub research questions will be answered, followed by the main research question.

Sub research question 1: Is the developed RCCPM tool able to effectively compare the results from RCCPM and traditional PM?

Yes, the case studies have shown that the developed RCCPM tool has been able to deliver a solid answer to the difference in lead time between RCCPM and traditional PM in sections 4.2 and 4.5. The RCCPM tool has also shown the ability to compose RCCPM progress reports in sections 4.3 and 4.6.

Sub research question 2: Is RCCPM better able to take risks and uncertainties into account than traditional PM?

Yes, traditionally project schedules are deterministic and each activity contains a hidden contingency margin; the amount of contingency is not visible in the schedule. RCCPM quantifies that contingency for each activity by performing extensive Monte Carlo simulations, taking into account uncertainties, risks and opportunities. These MC simulations have contributed to a reliable quantification of the P50 durations. By using the central limit theorem, contingencies are summed up and placed in a buffer at the end of the project. This enables the monitoring and controlling of variation throughout the project by using a fever chart. Traditional PM could also include probabilistic scheduling, but the earned value chart cannot be used to monitor and control variation.

Sub research question 3: Is RCCPM more effective in monitoring and controlling projects than traditional PM?

Yes, validation of the progress reports in section 4.11 has shown that the big majority of the sample size prefers the progress information RCCPM uses to the traditional % completion. 82% of the participants agreed that the fever chart provides better info on when to perform control (mitigation) actions compared to the earned value chart. When compared to traditional PM, the RCCPM progress report is said to give better information to make a decision for the upcoming week of the project, to provide clearer priorities and to be more helpful to get the project back on track. The fever chart dynamics in section 4.9 showed its ability to effectively cope with VOR’s.

Sub research question 4: Does RCCPM lead to earlier completion of projects in comparison with traditional PM?

Yes, the case studies have shown that by using RCCPM a lead-time reduction of about 10% is possible. This reduction can increase if the recommendations of the next section would be executed. Publicly shared experiences show an average lead-time reduction of 40%, but for a variety of reasons this seems to be impossible for the maritime industry as discussed in section 5.1.

Sub research question 5: Is there a difference in the application of RCCPM for complex specials and serial production? If yes, what is the difference?

No, during the case studies and literature review, there has not been found major differences between the application of (R)CCPM. The application of RCCPM in the case studies, consisting of a complex special fabrication and a serial production, has been very similar. Literature has shown that CCPM has been applied to many different industries with different project sizes and different project complexity levels.

Sub research question 6: What are the requirements for an organisation to adapt its PM method to RCCPM?

Most important is that the organisation is willing to improve its current processes, has a shared vision and support by senior management to implement RCCPM. Furthermore, there should be a lead implementer with knowledge about traditional PM, RCCPM and change management. Extra steps and data are needed for the shift from a deterministic to a probabilistic schedule as stated in subsection 4.10.1, and people should be trained to learn the differences between RCCPM and traditional PM.

All six sub research questions have been answered and they can now be deployed to answer the main research question. A viable alternative would be a PM method that has shown significant improvements compared to traditional PM, without the need to change much processes or bring high costs for implementing.

Main research question: Is Risk-based Critical Chain Project Management a viable alternative for traditional project management in the maritime industry?

Yes, RCCPM has shown significant improvements relative to traditional PM; it reduces the lead-time, it improves dealing with risks and uncertainties, and makes monitoring and controlling more effective. RCCPM can be applied in the maritime industry and the case studies are an example of this. No barriers have been found to introduce RCCPM on a day-to-day basis in organisations and projects similar to the ones investigated in this research. The RCCPM tool has used well-known, well-tested software, chosen after extensive comparisons of the available software, which makes it easy for other organisations to use.

5.3 Recommendations

This section describes the recommendations for further improvement and implementation of RCCPM.

Further research could have a look at intelligent scheduling algorithms for a multi-project environment, which are able to decrease the lead-time of a project by using big sets of constraints. Relevant for the shipbuilding industry are the Integrated Shipbuilding Planning Method (Rose, 2017) and Stottler Henke's scheduling software Aurora (Stottler Henke, 2017). Aurora for instance has shown to be able to shorten a schedule by 25% in comparison to Microsoft Project, because Aurora is better able to handle the complexity of the resource-constrained scheduling problem. This is done by including all kind of constraints, like the amount of resources available per time unit, the location of the activity, and activities that are not allowed to be executed concurrently. Intelligent algorithms are then able to take all of these constraints into account and come up with a superior schedule. A 25% shorter schedule would probably also lead to 25% improvement in the execution lead-time of the project, as people will adjust accordingly to the new schedule.

It is highly recommended to perform further research on the psychological effects of (R)CCPM. The psychological effects of eliminating multitasking and date driven behaviour have not been taken into account as the quantitative gain is hard to estimate without comparable scientific studies. It is believed that worker's motivation will increase, productivity will increase, stress rates decrease and burn out rates will decrease. If this is indeed the case, then the ±10% lead-time reduction of the case studies will grow.

Currently, project planners in a company have a modest position. Significant improvements could be made if the role of a project planner is extended to a project control advisor, by controlling schedule, costs, risks and scope. Project planners generally perform more projects a year than a project manager does, so planners could have a better look at the overall project management system. This makes them helpful advisors to the project manager and it enables them to spot and implement possible improvement and thereby increase the project management maturity.

During this research, it became more and more clear that a successful (R)CCPM implementation is constrained by the current contract types, even more because the maritime industry is known to have many co-makers (i.e. subcontractors). Contracts are usually lump sum or T&M (time and materials), but both have an incentive for the co-maker to write more hours than strictly needed or to wait with communicating errors by the contractor or client, so the co-maker can earn more money. Further research could look at a different type of contract, one that consists of a fixed fee and a performance fee. The fixed fee would be based on an estimation of the co-makers work, while the performance fee would be based on the performance of all co-makers together. Such a performance fee could be based on a weighted performance score, consisting of time, quality and safety performance. This provides an incentive for all partners on the project to work efficiently together in a collaborative team.

The last recommendation is to increase the public awareness of CCPM. To increase the amount of projects that are performed in a CCPM (related) method, more people should know about the existence of CCPM. Currently, CCPM is unknown to many companies and hardly ever taught at universities. Furthermore, the most often used scheduling software packages do not include the option to schedule a project according to the CCPM philosophy.

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Appendix 1: Scientific Paper

Discovering the Potential of Risk-based Critical Chain Project Management in the Maritime Industry

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Abstract

There is a never-ending quest to search for better ways of planning and controlling projects. Currently the majority of all projects are planned with the critical path method and controlled using earned value management. This way of planning and controlling projects has been used for decades now and can be seen as traditional project management (PM). This current PM paradigm does not work well enough for one-off projects. Risk assessment and risk management are not sufficiently covered in most standard PM methods. This paper looks at the potential of critical chain project management (CCPM) in combination with extensive risk management techniques for improving project performance. The paper will cover the development of a risk-based critical chain project management (RCCPM) methodology and its application to case studies at a shipyard. The study concludes that RCCPM is a viable alternative for traditional PM in the maritime industry. Improvements include a reduction of the lead-time, more effective monitoring and controlling, and improved dealing with risks and uncertainties.

Keywords:

Critical chain project management; project management; process improvement; project risk management; project planning; uncertainty; Monte Carlo simulation; shipbuilding.

1. Introduction

Critical path planning has not been modified significantly since its introduction in the 50's *(Shou & Yeo, 2000)*. The Project Management Body of Knowledge, as developed by the Project Management Institute, is seen as the standard work for traditional PM in this research and is an ANSI (American National Standards Institute) norm *(Project Management Institute, 2013)*.

Statistics show that 30% of the world's economic activities are arranged and performed in a project approach *(Turner, 2009)*. Many projects fail to deliver in terms of on time, within budget and with the promised quality/scope. Research has been carried out by others, which can support and elaborate this proposition.

KPMG conducted a survey with 52 respondents, showing that only 8% can say that the majority of their projects (more than 75%) deliver on time, within budget and with 90% realised scope. About 31% of the respondents indicated that 50-75% of their projects achieved the above stated criteria. The rest, which is the majority, completed only less than half of their projects as planned *(KPMG, 2015)*.

There are a variety of reasons why so many projects fail. Again, some studies have been done, with the most recent one asking the question: "Of the projects started in your organisation in the past 12 months that were deemed failures, what were the primary causes of those failures? (Select up to 3)" *(Project Management Institute, 2016)*, resulting in 17 different causes for project failure.

The question is then where to focus on with improving PM by using another method, as there are multiple alternative methodologies available. A lot of causes of project failures can be related to:

- Dealing with changes (events) during the project
- Inaccurate estimates of time and costs
- Management of risks and uncertainties
- Dealing with resources (dependencies, forecasting and limits)
- Procrastination

The solution of this research aims to improve PM on the five listed points. One of the available alternative methodologies that promise to have the potential to do that is called Critical Chain Project Management (CCPM). Publicly shared experiences claim an average lead-time reduction of about 40% *(Realization, 2017) (Kendall & Austin, 2012)*.

CCPM aims to eliminate six undesired effects which are commonly observed in traditional PM, those six are *(Leach, 1999)*:

1. Little actual activity positive variation
2. Failure to pass on positive variation
3. Project delay caused by activity path merging
4. Multitasking
5. Loss of focus
6. Excessive activity duration estimates

In general, risk assessment is not a part of the standard PM method, while it could solve much of the causes of project failures. Therefore, Monte Carlo simulation and event chain methodology will be a part of the solution. This changes CCPM into Risk-based Critical Chain Project Management (RCCPM).

The ultimate goal of this research is to find a way to better plan and control projects with a specific focus on the project's risks and uncertainties in order to improve project performance.

The main research question is stated as: Is Risk-based Critical Chain Project Management a viable alternative for traditional project management in the maritime industry?

RCCPM would prove to be viable in case project performance improves in comparison to traditional PM, not only in theory but also in reality. Project performance entails an on time, on budget and according to scope delivery. This would be the case if RCCPM can reduce the five listed causes of project failure. Another part of viable is the fact if an organisation can actually work according to the principles of RCCPM and if RCCPM can be applied to the maritime industry.

Sub research questions are also defined to make this main research question more specific and to aid in finding an answer to the main research question.

Answers to the main and sub research questions have been provided by means of five different activities.

1. A literature review into CCPM.
2. A study into the experiences of other organisations with CCPM.
3. Developing a RCCPM tool.
4. Applying the developed RCCPM tool to a set of case studies and comparing this with the traditional approach, both for lead-time reduction and difference in progress reporting.
5. A survey on the RCCPM type of progress reporting compared to traditional progress reports.

2. Methods

Critical Chain Project Management (CCPM) is the solution direction chosen in this study to improve project performance. CCPM is an alternative method of managing projects and is the PM application of the Theory of Constraints (TOC) as introduced by *Goldratt (1984, 1997)* in his books “The Goal” and “Critical Chain”. For a complete overview of CCPM the book Critical Chain Project Management by *Leach (2014)* can be recommended.

According to *Herroelen, Leus, & Demeulemeester (2002)* the fundamentals of CCPM are:

- 50% probability activity duration estimates
- No activity due dates
- No project milestones
- No multitasking
- Scheduling objectives are:
  - Minimise makespan
  - Minimise work in progress
- Determine a precedence and resource-feasible baseline schedule
- Identify the critical chain
- Aggregate uncertainty allowances into buffers
- Keep the baseline schedule and the critical chain fixed during project execution
- Determine an early start-based unbuffered projected schedule and report early completions (apply the roadrunner mentality)
- Use the buffers as a proactive warning mechanism during project execution

RCCPM makes an important difference between two types of variation, a theory which is made famous by *Deming (1986)* as “an understanding of variation”.

1. Common cause variation; variations inherently related to the overall project.
2. Special cause variation; variations related to a specific (set of) worker(s), machine(s) or location(s).

RCCPM makes use of the central limit theorem by *Rosenblatt (1956)* for the aggregation of individual tasks contingencies into a project buffer. *Steyn (2001)* concludes, “Aggregating project schedule contingency reserves is not common practice in traditional PM and applying the principle of aggregation could contribute significantly to the practice of PM”.

The three most important differences in CCPM planning compared to traditional are:

- P50 durations instead of low-risk durations
- 1 project buffer at the end of the project instead of a hidden buffer at each activity
- Late start schedule instead of early start

During execution, RCCPM advocates to follow a relay race approach consisting of:

- No milestones
- No multitasking
- Pass on your work as soon as possible

The progress is measured by a fever chart (see Figure 31) instead of an earned value chart and uses the amount of days needed instead of the percentage completion.

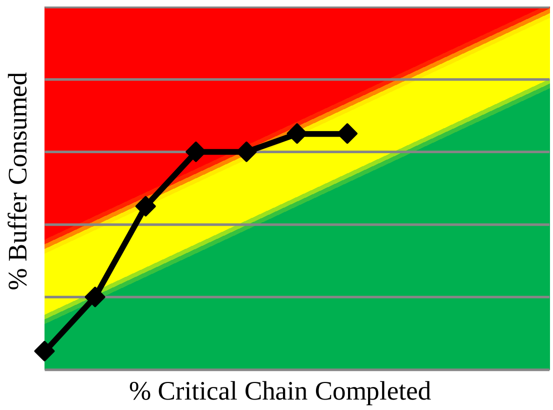

Figure 31: Fever chart

The general list of requirements for the RCCPM tool is as following:

- Easy to use and intuitive for both project planners and project managers.
- The entire range of CCPM features should be available.
- The ability to include uncertainties (common cause variations) and risks (special cause variations) in the project schedule.
- The ability to provide a distribution on the probability of finishing a project or activity on a set date.

- To provide a focus and aid in prioritization both in the planning and execution phase.
- Progress reports that are easy to make and that provide a clear overview of the status of a project.

An important difference between CCPM and RCCPM is the method for determining the P50 (focus) durations and the size of the project buffer. The current methods are too rough and often make buffers too large and P50 durations apocryphally small. However, a proper determination of the project buffer size is of utmost importance for the success of the project. This project buffer should not be too small, because the planned end date of the project buffer is the delivery date for the client and the risks of getting fines for late delivery should be avoided. A too large project buffer on the other hand would again lead to behaviour of using all of it (because of Parkinson's Law *(Gutierrez & Kouvelis, 1991; Parkinson, 1955)* and the student syndrome *(Rand, 2000)*), resulting in uncompetitive proposals. This is why advanced risk analysis techniques are applied, namely Monte Carlo simulation *(Kwak & Ingall, 2007)* and event chain methodology *(Virine & Trumper, n.d.)*.

Off-the-shelf software is chosen for CCPM and risk elements as part of the RCCPM tool. The software is chosen after identifying the functional and technical requirements, identifying the software packages that could provide either CCPM or risk functionalities, followed by an assessment and decision-making process using the analytical hierarchy process *(Saaty, 2008)*. The selected software is ProChain by ProChain Solutions for the CCPM functionalities and RiskyProject by Intaver Institute for the risk functionalities.

On a high level, the RCCPM tool in the planning phase looks as following:

1. Basic schedule set-up (similar to traditional PM)
2. Eliminate milestones & buffers
3. Change each task to late start
4. Define uncertainties, risks and opportunities
5. Perform Monte Carlo simulations
6. Determine the P50 durations
7. Calculate and place the buffer

During the execution phase, the high level process flow is as following:

1. Collect remaining durations of activities
2. Check buffer status
3. Review reasoning for buffer consumption
4. Take action according to buffer status
5. Communicate and focus on baton tasks
6. Compose a progress report

3. Results and discussion

The RCCPM tool has been successfully applied to two case studies of a shipyard. Case 1 involves the fabrication of special offshore equipment, while case 2 consist of a serial production of offshore wind turbine foundations.

Case study 1 has shown an estimated lead-time reduction of 10%, while case study 2 reached 9%. This is substantially less than the average reduction of 40% that CCPM consultancy and software companies claim. There are a variety of explanations for this difference:

- The possible gains from eliminating multitasking, the student syndrome, Parkinson's Law and comparable psychological effects during project execution are hard to quantify and are therefore not part of the 9-10% lead-time reduction. It is to be expected that a real-life case study shows a bigger lead-time reduction.
- The results are quite dependent on the assumptions about uncertainty. If we assume more uncertainty in our estimations than the lead-time reduction will be bigger as well.
- The 9% reduction in case 2 is compared to the traditional schedule. This traditional schedule already contained buffers to protect the project against risks and uncertainties. The reduction would have been bigger if there were no buffers in the traditional schedule.
- Those companies that have said to achieve 40% lead-time reduction, cut their durations

in half (the focus duration is only 50% of the low-risk duration). This seems to be impossible in the maritime industry, because activities have a technical minimum required duration that is constrained by for instance the speed of a ship, the amount of machine operations or the amount of people that can (safely) work in an area. For these cases, the average difference between focus and low-risk durations is 15-20% instead of 50%.

- Literature assumes projects to be scheduled at P95 or P90. In the maritime industry, this number is substantially lower, probably about P75. A lower confidence level means that there is less to "win" by scheduling at P50.
- The 40% lead-time reduction number comes from publicly shared experiences by CCPM consultancy and software companies; this number is probably highly biased as only the best experiences are openly shared in order to sell their services.
- These cases and the maritime industry in general works with many co-makers (subcontractors), if they keep working according to their traditional PM paradigm than the reduction cannot reach its global optimum. An alternative method of contracting with a shared performance fee can help.

The progress reports are validated by a questionnaire amongst 18 people at Delft University of Technology. Participants largely agreed that the fever chart's three-colour system is superior in knowing when to perform control actions compared to the earned value chart. Participants also largely agreed that an estimation of the amount of days an activity still needs (used for the fever chart) is preferred over the estimated percentage of completion (used for the earned value chart). Lastly, both the RCCPM and traditional progress reports are assessed on a set of criteria (see Figure 32).

Figure 32 shows that the most important criterion is 'the best information to make a decision for the upcoming week of the project'; RCCPM wins this one by 17 percentage points. On the other hand, the second most important criterion 'clarity about the status' is won by traditional with 17 percentage points. This, together with the criterion 'quickest overview' can be explained by the fact that the students were already familiar with earned value. RCCPM is clearly preferred for the criteria 'clearest priorities' and 'most helpful to get the project back on track'. The criteria 'most information' and 'best focus' are thought to be not very important for a progress report.

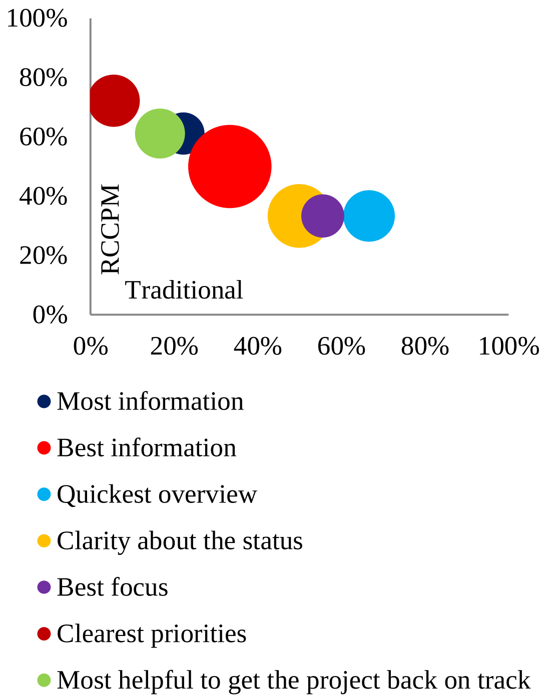

Figure 32: Assessment of the progress reports

4. Conclusions

The developed RCCPM tool has been able to effectively compare the results from RCCPM and traditional PM. The case studies have shown that the tool can deliver a solid answer to the difference in lead time and it has the ability to compose RCCPM progress reports.

RCCPM has shown to be better able in taking risks and uncertainties into account compared to traditional PM. Traditionally, project schedules are deterministic and each activity contains a hidden contingency margin; the amount of contingency is not visible in the schedule.

RCCPM quantifies that contingency for each activity by performing extensive Monte Carlo simulations, taking into account uncertainties, risks and opportunities. These MC simulations have contributed to a reliable quantification of the P50 durations. By using the central limit theorem, contingencies are summed up and placed in a buffer at the end of the project. This enables the monitoring and controlling of variation throughout the project by using a fever chart. Traditional PM could also include probabilistic scheduling, but the earned value chart cannot be used to monitor and control variation.

RCCPM has shown to be more effective in monitoring and controlling projects than traditional PM. Validation of the progress reports has shown that the big majority of the sample size prefers the progress information RCCPM uses to the traditional % completion. 82% of the participants agreed that the fever chart provides better info on when to perform control (mitigation) actions compared to the earned value chart. When compared to traditional PM, the RCCPM progress report is said to give better information to make a decision for the upcoming week of the project, to provide clearer priorities and to be more helpful to get the project back on track. The fever chart has showed its ability to effectively cope with VOR's.

RCCPM has shown in the case studies a lead-time reduction of 10% compared to traditional PM. Publicly shared experiences show an average lead-time reduction of 40%, but for a variety of reasons this seems to be impossible for the maritime industry.

There has not been found any major differences between the application of RCCPM to complex specials and serial production case studies. Literature has shown that CCPM has been applied to many different industries with different project sizes and different project complexity levels.

Organisations that want to adapt its PM method to RCCPM should most importantly be willing to improve their current processes. Other important requirements are a shared vision and support by senior management to implement RCCPM. Furthermore, there should be a lead implementer with knowledge about traditional PM, RCCPM and change management. Extra steps and data are needed for the shift from a deterministic to a probabilistic schedule, and people should be trained to learn the differences between RCCPM and traditional PM.

All sub research questions have been answered and they can be deployed to answer the main research question; Is Risk-based Critical Chain Project Management a viable alternative for traditional project management in the maritime industry? A viable alternative would be a PM method that has shown significant improvements compared to traditional PM, without the need to change much processes or bring high costs for implementing.

The answer to the main research question is yes, RCCPM has shown significant improvements relative to traditional PM; it reduces the lead-time, it improves dealing with risks and uncertainties, and makes monitoring and controlling more effective. RCCPM can be applied in the maritime industry and the case studies are an example of this. No barriers have been found to introduce RCCPM on a day-to-day basis in organisations and projects similar to the ones investigated in this research. The RCCPM tool has used well-known, well-tested software, chosen after extensive comparisons of the available software, which makes it convenient for other organisations to use.

It is highly recommended to perform further research on the psychological effects of (R)CCPM. The psychological effects of eliminating multitasking and date driven behaviour have not been taken into account as the quantitative gain is hard to estimate without comparable scientific studies. It is believed that worker's motivation will increase, productivity will increase, stress rates decrease and burn out rates will decrease. If this is indeed the case, then the ±10% lead-time reduction of the case studies will grow.

The final recommendation is to increase the public awareness of CCPM. To increase the amount of projects that are performed in a CCPM (related) method, more people should know about the existence of CCPM. Currently, CCPM is unknown to many companies and hardly ever taught at universities. Furthermore, the most often used scheduling software packages do not include the option to schedule a project according to the CCPM philosophy.

5. Acknowledgements

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Appendix 2: Theoretical Comparison of CCPM and Traditional PM

Table 11: Comparison between traditional PM and CCPM on a philosophical level (Lechler et al., 2005a)

Perspective	Traditional PM	CCPM
Theory	• Systems Theory • Graph Theory	• Systems Theory • Graph Theory • Theory of Constraints (TOC)
Goals	• Minimize duration of single project under resource constraints • Satisfy the triple constraints of time, cost, and scope	• Minimize duration of single project under resource constraints • Maximize project throughput in multi project environments • Satisfy the triple constraints of time, cost, and scope with special emphasis on meeting the due date • Adopt a satisficing approach
Focus of attention	• Single project perspective (primarily) • Set a project completion time and determine which activities require particular attention to avoid delaying project completion • Local systems perspective	• Systems perspective—both single and multiple project environments • Set a project completion time and determine, under explicit consideration of uncertainty, which activities require particular attention to avoid delaying project completion • Global systems perspective
Uncertainty	• Contingency plans to protect against external events based on risk analysis and Monte Carlo simulation • Local protection against uncertainty •Trade-offs between the triple constraints	• Contingency plans to protect against external events based on risk analysis and Monte Carlo simulation • Global protection against uncertainty • Trade-offs between the triple constraints are not emphasized; CC attempts to avoid the need for trade-offs
Resource management	• Solve the Resource-Constrained Scheduling Problem (RCSP) to develop a baseline schedule • Maximize utilization of all resources	• Solve the RCSP to develop a baseline schedule (as for CP, but including buffers) • Maximize utilization of the bottleneck resource(s)
Behavioural issues	• The human-side of project management only implicitly addressed	• Reduce activity times to counteract individual tendencies to delay task execution (Parkinson's Law and Student Syndrome)

Table 12: Comparison between traditional PM and CCPM on a single project planning level (Lechler et al., 2005a)

Perspective	Traditional PM	CCPM
Goals	• Minimize project duration • Protect the due date	• Minimize project duration • Use buffers to protect the due date • Minimize work-in-process (WIP)
Focus of attention	• Critical path • Identify calendar dates for project milestones	• Critical chain • No project milestone calendar dates except where externally imposed
Uncertainty	• Activity estimates might contain contingency margins • No project buffer • CP protected to some extend by float • Schedule activities at their early start time	• Remove contingency margins from activity estimates • Aggregate contingency margins on the critical chain into a project buffer • Add feeding buffers where non-critical paths join the critical chain • Schedule activities at their latest start times to reduce WIP
Resource management	• Determine a precedence and resource feasible baseline schedule	• Determine a precedence and resource feasible baseline schedule
Scheduling	• Solve the RCSP problem to resolve resource conflicts and estimate the critical path	• Solve the RCSP problem to resolve resource conflicts and estimate the critical chain • Use as late as possible start dates for the activities • Introduce project buffers and feeding buffers
Behavioural issues	• Activity estimates might contain contingency margins	• Avoid the student syndrome and Parkinson’s law

Table 13: Comparison between traditional PM and CCPM on a single project execution and control level (Lechler et al., 2005a)

Perspective	Traditional PM	CCPM
Focus of attention	• Manage to the calendar dates of the critical path activities • Meet project milestones	• Keep the baseline schedule and critical chain fixed during execution
Uncertainty	• Use available float • Trade-off decisions between budget, scope, and schedule	• Buffer management
Resource management	• Coordinate resources along the critical path • No explicit position on multitasking	• Coordinate resources by heeding buffer warnings • Avoid multitasking
Execution and rescheduling	• No single guideline—many heuristics	• Use road-runner paradigm—execute activities as soon as feasible—except for gating activities
Monitoring metrics	• Monitor and report activity start and finish times • Monitor progress towards project milestones • Earned value (EV) reporting	• No activity due dates • Report penetration of buffers • No project milestones except where externally imposed • EV reporting difficult but not excluded
Behavioural issues	• Activity performers are held responsible for timely activity completion	• Responsibility for activity delays not clarified

Table 14: Comparison between traditional PM and CCPM on a multi project planning level (Lechler et al., 2005a)

Perspective	Traditional PM	CCPM
Goals	• Minimize project duration	• Maximize systems throughput
Focus of attention	• Performance of individual projects	• Performance of multiple project system constraint resource • Reduce WIP
Uncertainty	• Not explicitly addressed	• Introduce drum and capacity buffers
Resource management	• Maximize resource utilization of all resources • Multitasking not explicitly addressed	• Maximize resource utilization of constraint resources • Do not allow multitasking
Scheduling	• Several project prioritization rules	• Stagger projects along the systems constraint using drum and capacity buffers • Prioritize projects • Resolve resource conflicts on the systems level
Behavioural issues	• Not explicitly addressed	• Avoid multitasking

Table 15: Comparison between traditional PM and CCPM on a multi project execution and controlling level (Lechler et al., 2005a)

Perspective	Traditional PM	CCPM
Focus of attention	• Avoid variation on critical path	• Support the bottleneck resource
Uncertainty	• As for single project case	• Drum and capacity buffers
Resource management	• Maximize utilization of all available resources	• Maximize utilization of bottleneck resource
Execution and rescheduling	• Different prioritization rules	• Manage the total system using drum buffers • Drum buffer rope to control for new entering projects
Monitoring metrics	• Earned value (EV) reporting • No explicit multi project metrics	• EV reporting • Systems Metrics: Number of projects finished (throughput), WIP
Behavioural issues	• Not explicitly addressed • Accountability for due dates clearly regulated	• Avoid multitasking • Accountability not clear

Appendix 3: Current Process Flow for Scheduling and Progress Reporting

This appendix cannot be disclosed in this repository version because of confidentiality reasons.

Appendix 4: AHP Tables

Table 16: Assessment of CCPM software

	Lynx A-Dato	ProChain ProChain Solutions
5. Easy to use/learn	Not easy as it is stand-alone software without an intuitive interface.	Easy, fully integrated as add-in to Microsoft Project.
6. Well known and applied frequently	Not well known, only small-scale applications since 2010.	Very well known, first to work with CCPM. Hundreds of customers since 1997.
7. Track record for large, complex projects	No such applications known.	Many of such applications known.
8.A Critical Chain	Automatically identified and indicated.	Automatically identified and indicated.
8.B Project buffer	Yes, can also be excluded.	Yes, can also be excluded.
8.C Feedings buffers	Yes, can also be excluded.	Yes, can also be excluded.
8.D Buffer sizing methods	Only % can be given as input.	Both amount of days and % can be given as input.
8.E Fever chart	Yes, but hard to find and without customisable thresholds.	Yes, with customisable thresholds.

Table 17: Pairwise comparisons between CCPM software and their strength in meeting each requirement

5	ProChain	Lynx	Priority
ProChain	1	5	0.83
Lynx	1/5	1	0.17

8.B	ProChain	Lynx	Priority
ProChain	1	1	0.50
Lynx	1	1	0.50

6	ProChain	Lynx	Priority
ProChain	1	7	0.88
Lynx	1/7	1	0.13

8.C	ProChain	Lynx	Priority
ProChain	1	1	0.50
Lynx	1	1	0.50

7	ProChain	Lynx	Priority
ProChain	1	8	0.89
Lynx	1/8	1	0.11

8.D	ProChain	Lynx	Priority
ProChain	1	7	0.88
Lynx	1/7	1	0.13

8.A	ProChain	Lynx	Priority
ProChain	1	1	0.50
Lynx	1	1	0.50

8.E	ProChain	Lynx	Priority
ProChain	1	4	0.80
Lynx	1/4	1	0.20

Table 18: Pairwise comparisons of all CCPM requirements with respect to their importance to reaching the goal

	5	6	7	8.A	8.B	8.C	8.D	8.E	Priority
5	1	5	3	2	3	6	2	3	0.28
6	1/5	1	1/3	1/2	1/3	1	1/5	1/3	0.04
7	1/3	3	1	2	1	3	1/3	1	0.11
8.A	1/2	2	1/2	1	1	4	1/3	1	0.10
8.B	1/3	3	1	1	1	4	1/3	1	0.10
8.C	1/6	1	1/3	1/4	1/4	1	1/5	1/4	0.03
8.D	1/2	5	3	3	3	5	1	3	0.24
8.E	1/3	3	1	1	1	4	1/3	1	0.10

Table 19: Assessment of risk analysis software

	@Risk Palisade	**Full Monte Barbecana**	**RiskyProject Intaver Institute**
5. Easy to use/learn	Intuitive, but not optimal as it's not an add-in for MS Project	Add-in, but no clear menus	Add-in and clear, intuitive menus
6. Well known and applied frequently	Very well known	Not well known	Moderately well known
7.A Statistical distributions	83 distributions	5 distributions	13 distributions
7.B Inclusion of risks	No	No	Yes, extensive
7.C Histogram with results	Yes, clear	Yes, not very clear	Yes, clear
7.D Sensitivity analysis	Yes, clear	Yes, not very clear	Yes, clear

Table 20 Pairwise comparisons between risk analysis software and their strength in meeting each requirement

5	@Risk	Full Monte	RiskyProject	Priority
@Risk	1	1	1/5	0.14
Full Monte	1	1	1/5	0.14
RiskyProject	5	5	1	0.71

6	@Risk	Full Monte	RiskyProject	Priority
@Risk	1	9	4	0.72
Full Monte	1/9	1	1/4	0.07
RiskyProject	1/4	4	1	0.22

7.A	@Risk	Full Monte	RiskyProject	Priority
@Risk	1	5	3	0.64
Full Monte	1/5	1	1/3	0.11
RiskyProject	1/3	3	1	0.26

7.B	@Risk	Full Monte	RiskyProject	Priority
@Risk	1	1	1/9	0.09
Full Monte	1	1	1/9	0.09
RiskyProject	9	9	1	0.82

7.C	@Risk	Full Monte	RiskyProject	Priority
@Risk	1	5	1	0.46
Full Monte	1/5	1	1/5	0.09
RiskyProject	1	5	1	0.46

7.D	@Risk	Full Monte	RiskyProject	Priority
@Risk	1	5	1	0.46
Full Monte	1/5	1	1/5	0.09
RiskyProject	1	5	1	0.46

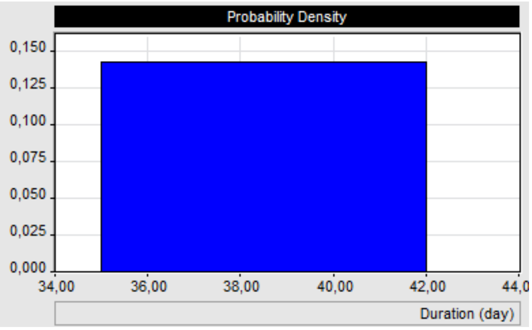
Table 21: Pairwise comparisons of all risk analysis requirements with respect to their importance to reaching the goal

	5	6	7.A	7.B	7.C	7.D	Priority
5	1	5	3	1	6	3	0.32
6	1/5	1	1/2	1/5	1	1/3	0.06
7.A	1/3	2	1	1/4	3	1	0.11
7.B	1	5	4	1	5	3	0.33
7.C	1/6	1	1/3	1/5	1	1/3	0.05
7.D	1/3	3	1	1/3	3	1	0.13

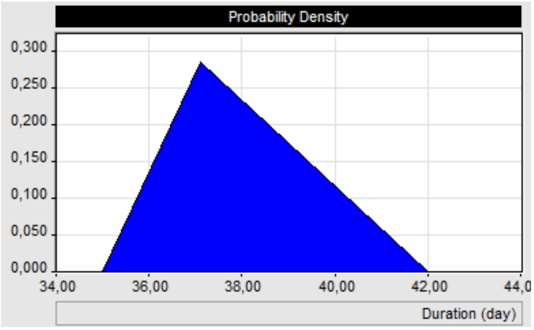
Appendix 5: Probability Distributions

Table 22: Possible distributions

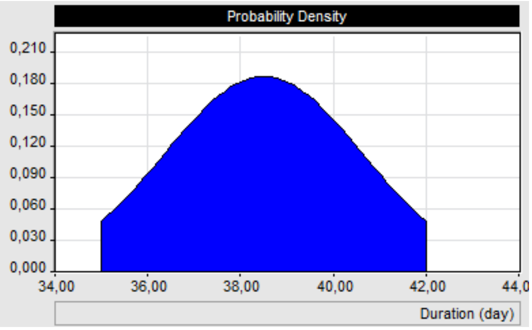
Uniform



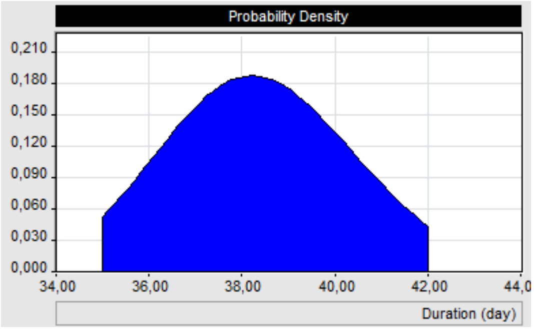
Triangular



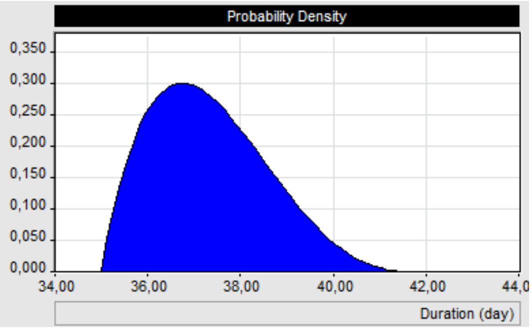
Normal



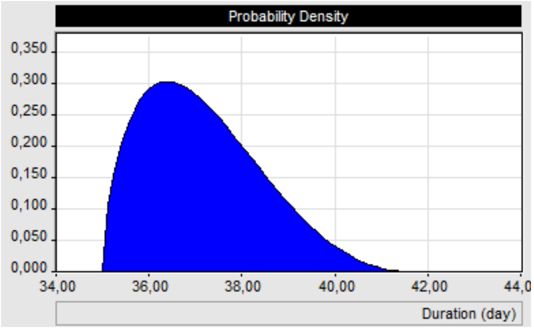
Lognormal



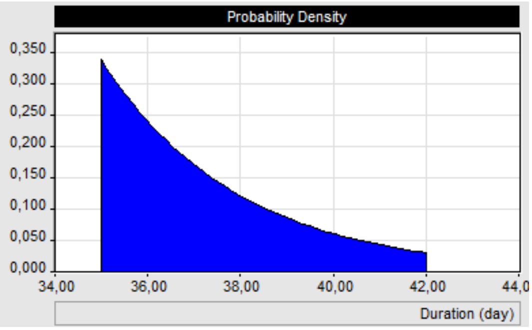
Beta



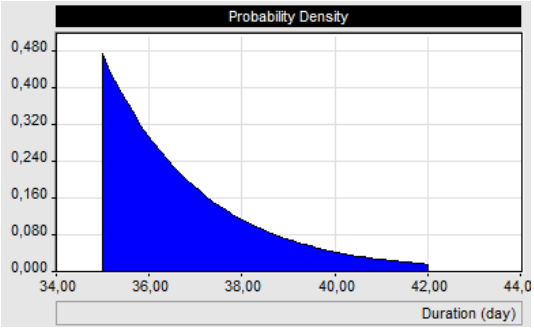
BetaPert



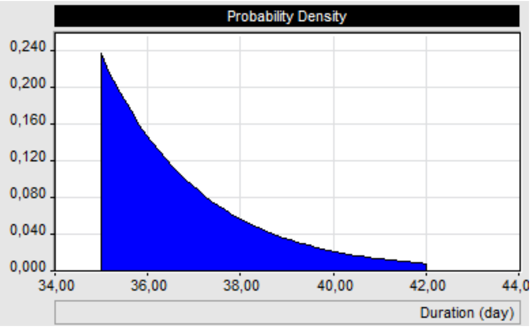
Gamma



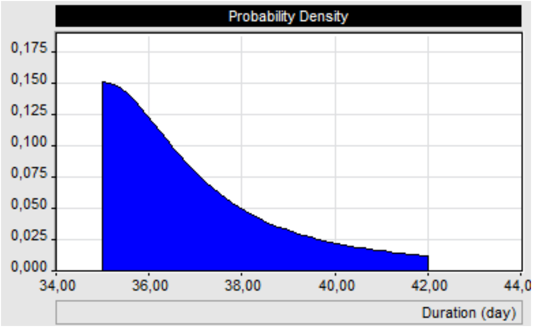
Exponential



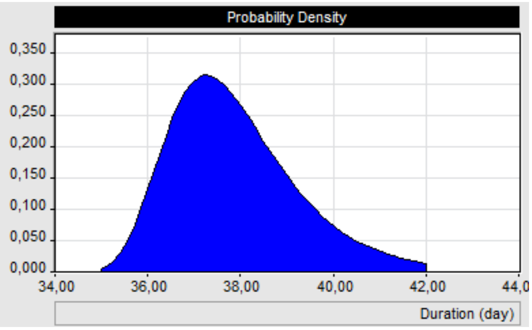
Laplace



Cauchy



Gumbel



Rayleigh

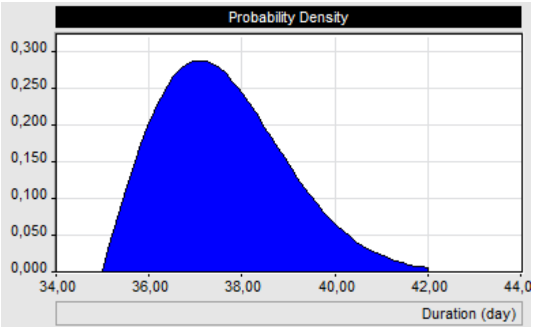


Table 23: Possible distributions

Distribution	Usage
Uniform	If there is an equal probability between the low and high durations.
Triangular	If the distribution is skewed and simplicity is wished.
Normal	If the distribution is symmetrical.
Lognormal	If the log of the distribution is symmetrical.
Beta	Can be used for a wide range of distributions, by adjusting the α and β values.
BetaPert	Can be seen as an in-between of triangular and beta.
Gamma	If the low duration is the best-case scenario; shorter is not possible due to some constraint, once that constraint is passed, there is directly a high change of finishing.
Exponential	Similar to gamma.
Laplace	Similar to gamma.
Cauchy	Similar to gamma.
Gumbel	If the distribution is skewed towards the low duration.
Rayleigh	Similar to Gumbel.

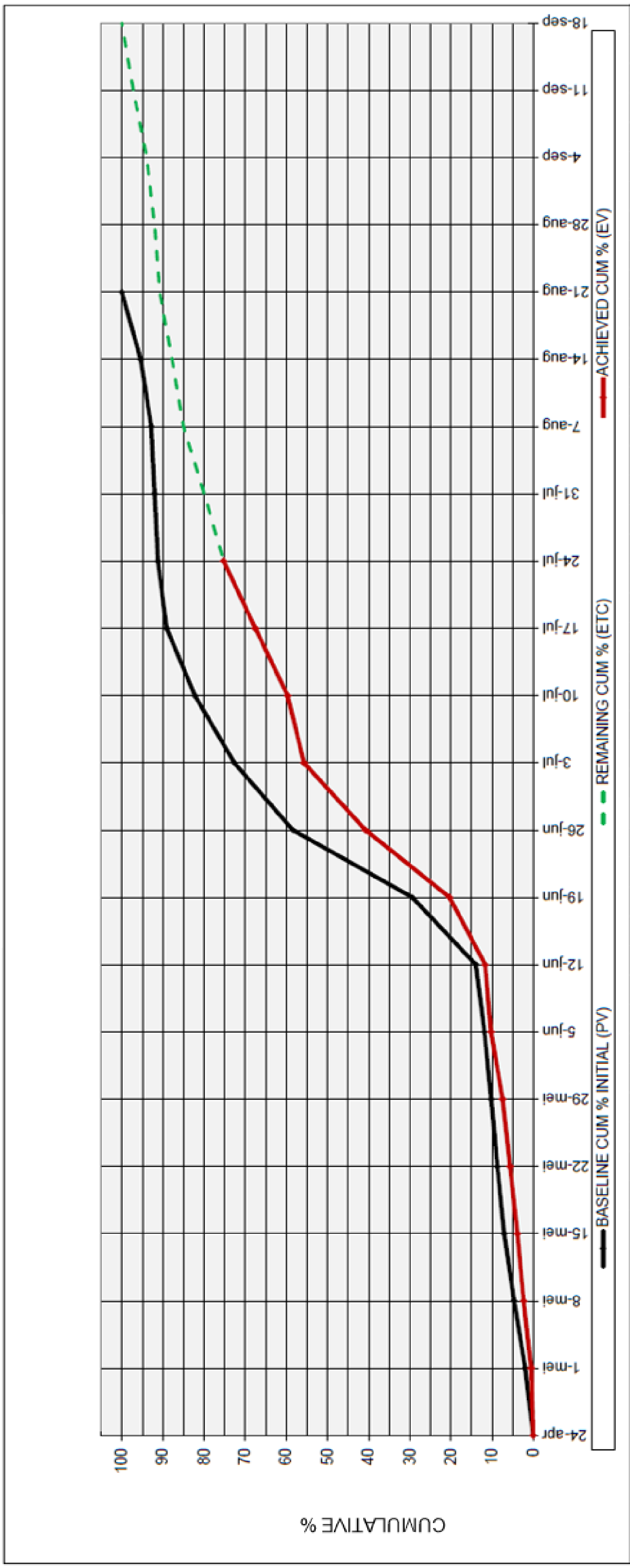
Appendix 6: Combined Traditional & RCCPM Schedule Case 1

This appendix cannot be disclosed in this repository version because of confidentiality reasons.

Appendix 7: Traditional Progress Report Case 1

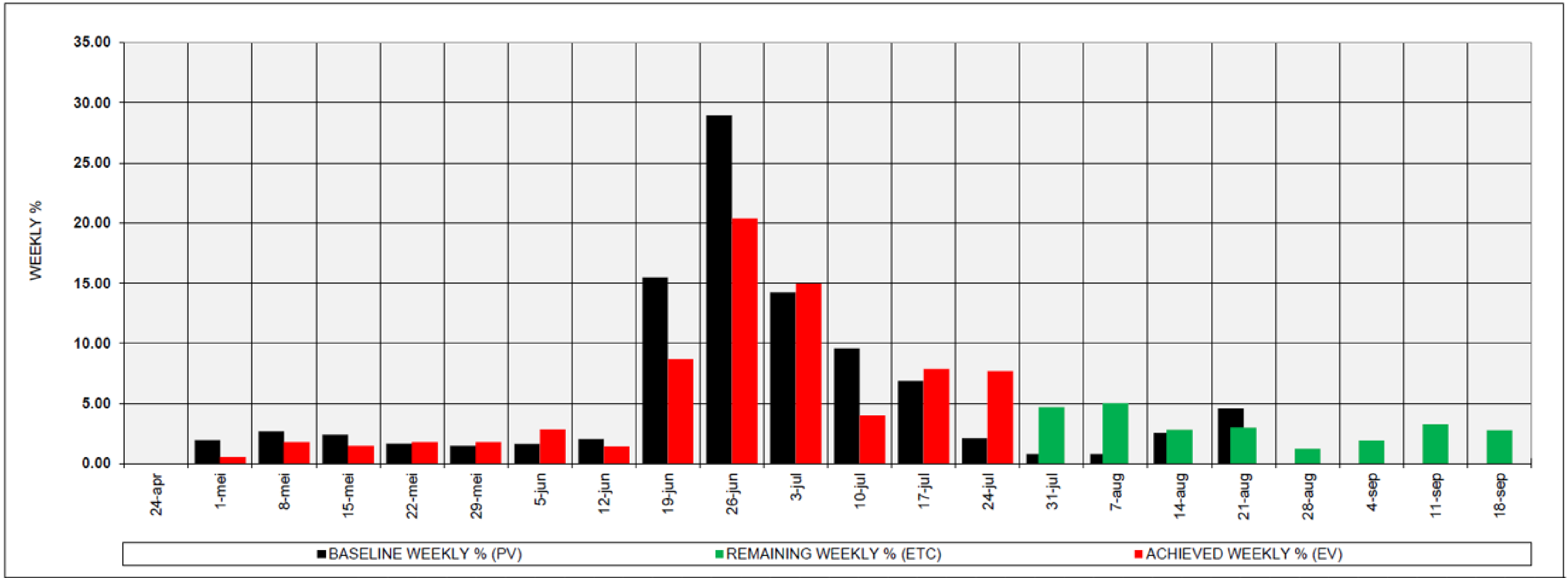
PROGRESS REPORT SHEET
PERIOD INCL. : WK29 - 2016
CUT-OFF DATE : 24 juli 2016
PRINT DATE : 28 juli 2016

Earned value chart



CUT-OFF DATE	24-apr-16	1-mei-16	8-mei-16	15-mei-16	22-mei-16	29-mei-16	5-jun-16	12-jun-16	19-jun-16	26-jun-16	3-jul-16	10-jul-16	17-jul-16	24-jul-16	31-jul-16	7-aug-16	14-aug-16	21-aug-16	28-aug-16	4-sep-16	11-sep-16	18-sep-16	25-sep-16	2-okt-16	9-okt-16	16-okt-16	23-okt-16	30-okt-16	6-nov-16	13-nov-16	20-nov-16	27-nov-16	4-dec-16	11-dec-16	18-dec-16	25-dec-16	1-jan-17	8-jan-17	15-jan-17	22-jan-17	29-jan-17
PERIOD INCL.WK	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4
BASELINE CUM % INITIAL (PV)	0.00	1.97	4.66	7.06	8.72	10.22	11.86	13.93	29.43	58.39	72.66	82.24	89.12	91.23	92.05	92.87	95.41	100.00																							
ACHIEVED CUM % (EV)	0.00	0.54	2.33	3.83	5.62	7.41	10.26	11.68	20.38	40.77	55.71	59.71	67.56	75.26																											
REMAINING CUM % (ETC)	0.00	0.54	2.33	3.83	5.62	7.41	10.26	11.68	20.38	40.77	55.71	59.71	67.56	75.26	79.98	85.00	87.83	90.81	92.03	93.97	97.23	100.00																			

Histogram



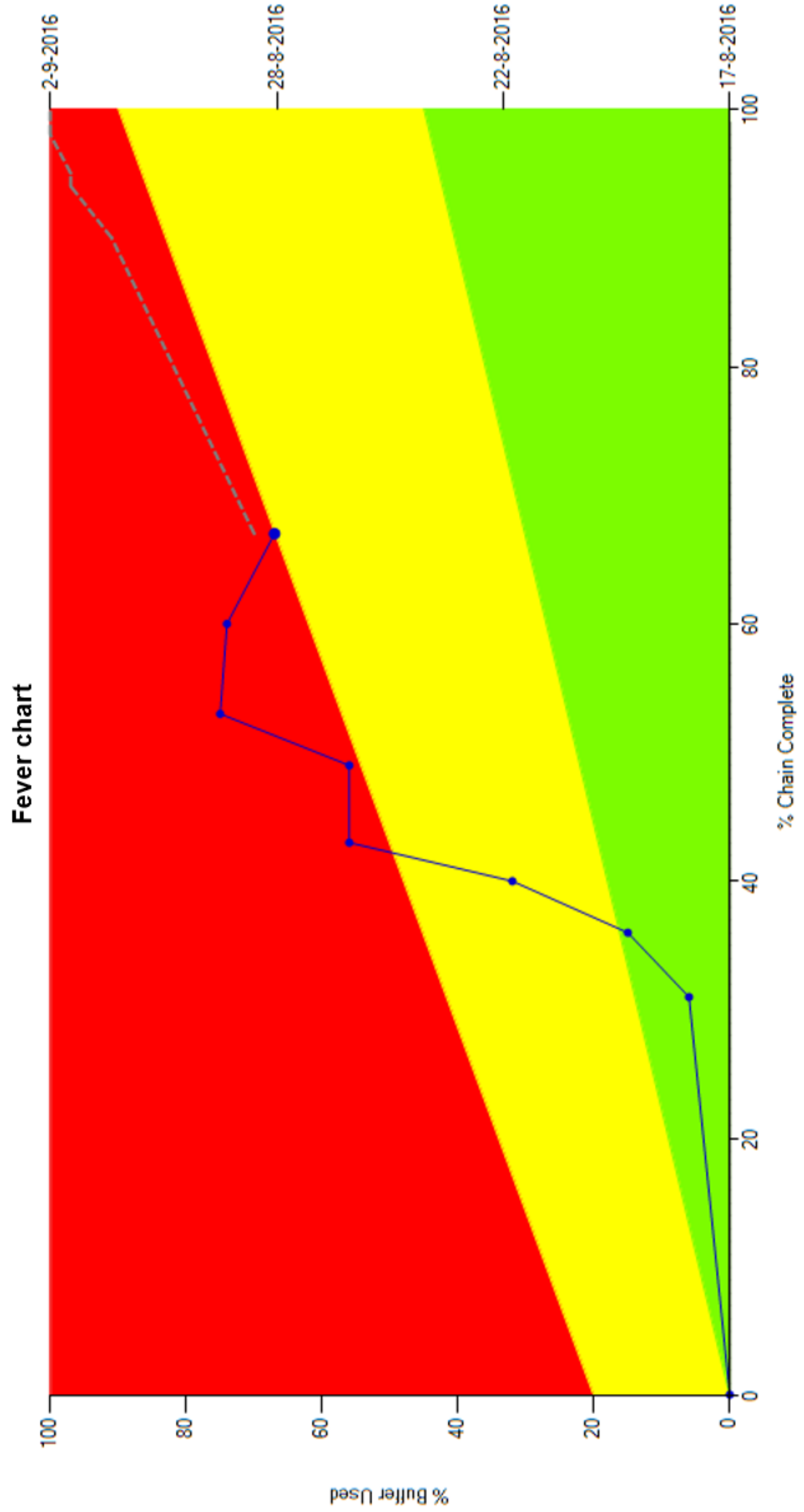
CUT-OFF DATE	24-apr-16	1-mei-16	8-mei-16	15-mei-16	22-mei-16	29-mei-16	5-jun-16	12-jun-16	19-jun-16	26-jun-16	3-jul-16	10-jul-16	17-jul-16	24-jul-16
PERIOD INCL.WK	16	17	18	19	20	21	22	23	24	25	26	27	28	29
BASELINE WEEKLY % (PV)		1.97	2.69	2.40	1.66	1.50	1.64	2.07	15.49	28.96	14.27	9.58	6.88	2.11
ACHIEVED WEEKLY % (EV)		0.54	1.79	1.50	1.79	1.79	2.84	1.43	8.70	20.39	14.94	4.00	7.84	7.70
REMAINING WEEKLY % (ETC)														

CUT-OFF DATE	31-jul-16	7-aug-16	14-aug-16	21-aug-16	28-aug-16	4-sep-16	11-sep-16	18-sep-16	25-sep-16	2-okt-16	9-okt-16	16-okt-16	23-okt-16	30-okt-16
PERIOD INCL.WK	30	31	32	33	34	35	36	37	38	39	40	41	42	43
BASELINE WEEKLY % (PV)	0.82	0.82	2.53	4.59										
ACHIEVED WEEKLY % (EV)														
REMAINING WEEKLY % (ETC)	4.72	5.03	2.82	2.98	1.22	1.94	3.26	2.77						

CUT-OFF DATE	6-nov-16	13-nov-16	20-nov-16	27-nov-16	4-dec-16	11-dec-16	18-dec-16	25-dec-16	1-jan-17	8-jan-17	15-jan-17	22-jan-17	29-jan-17
PERIOD INCL.WK	44	45	46	47	48	49	50	51	52	1	2	3	4
BASELINE WEEKLY % (PV)													
ACHIEVED WEEKLY % (EV)													
REMAINING WEEKLY % (ETC)													

Appendix 8: RCCPM Progress Report Case 1

Status date	Colour	Buffer used [%]	Chain complete [%]	RBCI (Relative Buffer Consumption Index)	Buffer left [days]	Chain left [days]	Original buffer [days]	Original chain [days]	Baton task
24-7-16	Red/ Yellow	67%	67%	1.0	5.6	49	17	151	Fabrication upper frame: PS aft corner



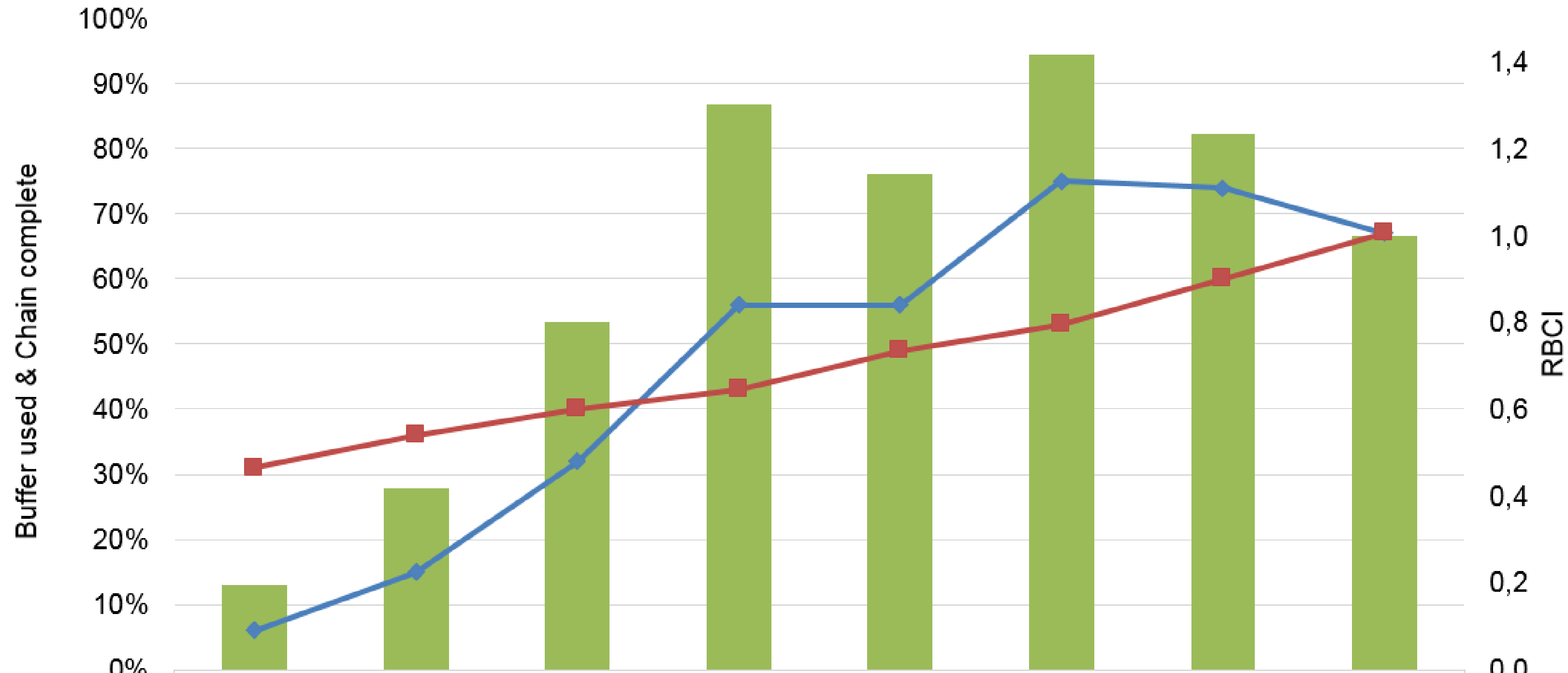
3 most crucial tasks

1. Fabrication upper frame: PS aft corner
2. Fabrication upper frame: Aft cheeks (sheave 2)
3. Fabrication sheave hatch: In-situ machining

3 most critical risks

1. Unavailability of qualified personnel during summer
2. Test failed
3. Scarce machinery failure

Date based chart



	5-6-16	12-6-16	19-6-16	26-6-16	3-7-16	10-7-16	17-7-16	24-7-16
RBCI	0,19	0,42	0,80	1,30	1,14	1,42	1,23	1,00
Buffer used [%]	6%	15%	32%	56%	56%	75%	74%	67%
Chain complete [%]	31%	36%	40%	43%	49%	53%	60%	67%

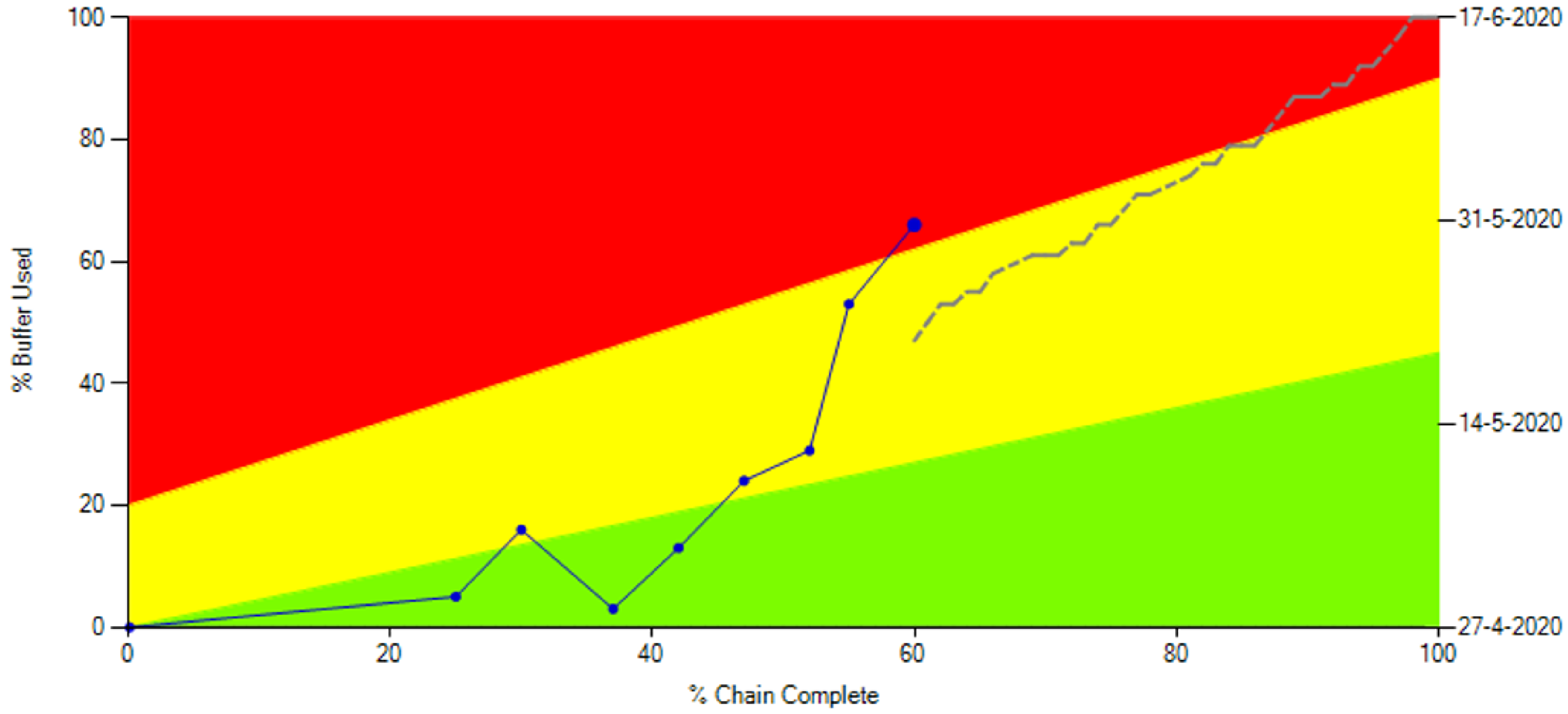
Appendix 9: Combined Traditional & RCCPM Schedule Case 2

This appendix cannot be disclosed in this repository version because of confidentiality reasons.

Appendix 10: RCCPM Progress Report Case 2

Status date	Colour	Buffer used [%]	Chain complete [%]	RBCI (Relative Buffer Consumption Index)	Buffer left [days]	Chain left [days]	Original buffer [days]	Original chain [days]	Baton task
1-11-19	Red	66%	60%	1.10	18	205	52	516	Assembly jacket 1.1

Fever chart



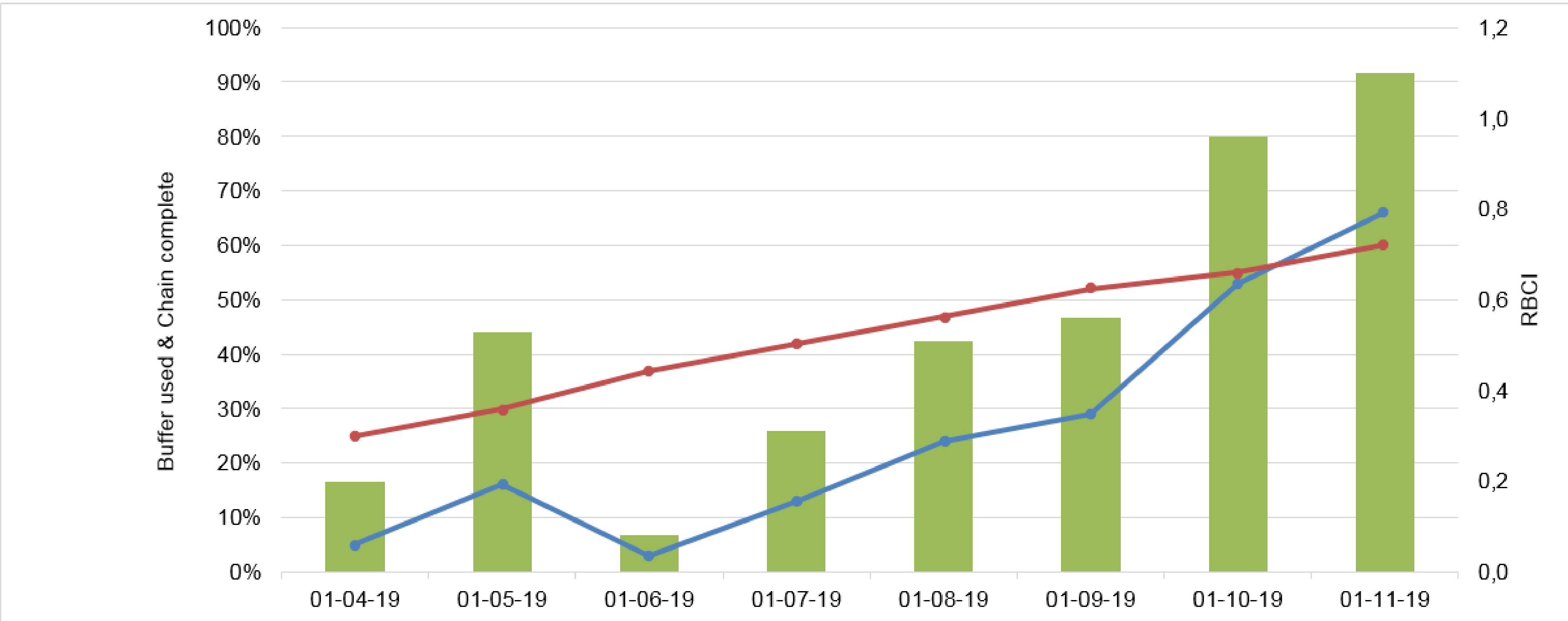
3 most crucial tasks

1. Batch 6: Assembly of panels
2. Trip 2: Sailing to DVR
3. Batch 4: Outfitting steel

3 most critical risks

1. Bad weather
2. Scarce machinery failure
3. Unavailability of major equipment

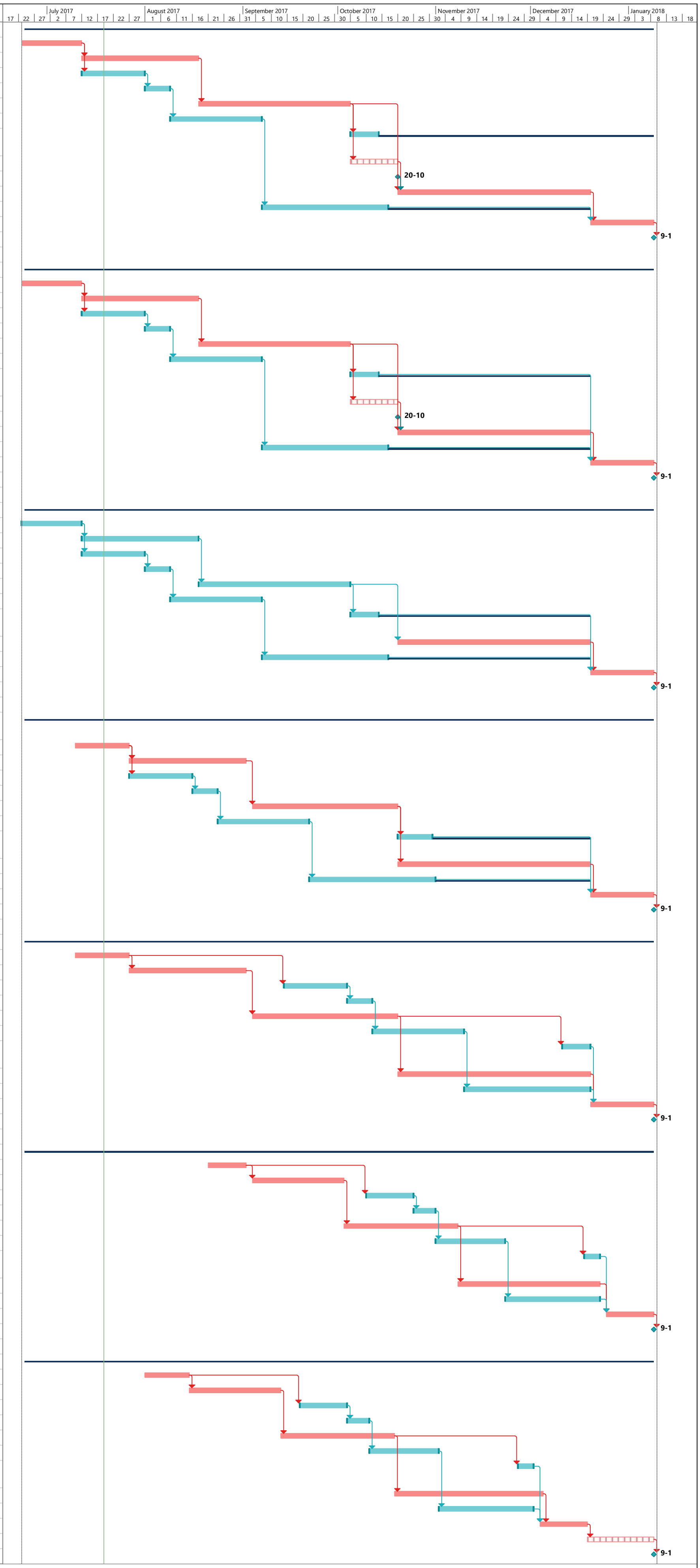
Date based chart



	1-04-19	1-05-19	1-06-19	1-07-19	1-08-19	1-09-19	1-10-19	1-11-19
RBCI	0,2	0,53	0,08	0,31	0,51	0,56	0,96	1,1
Buffer used [%]	5%	16%	3%	13%	24%	29%	53%	66%
Chain complete [%]	25%	30%	37%	42%	47%	52%	55%	60%

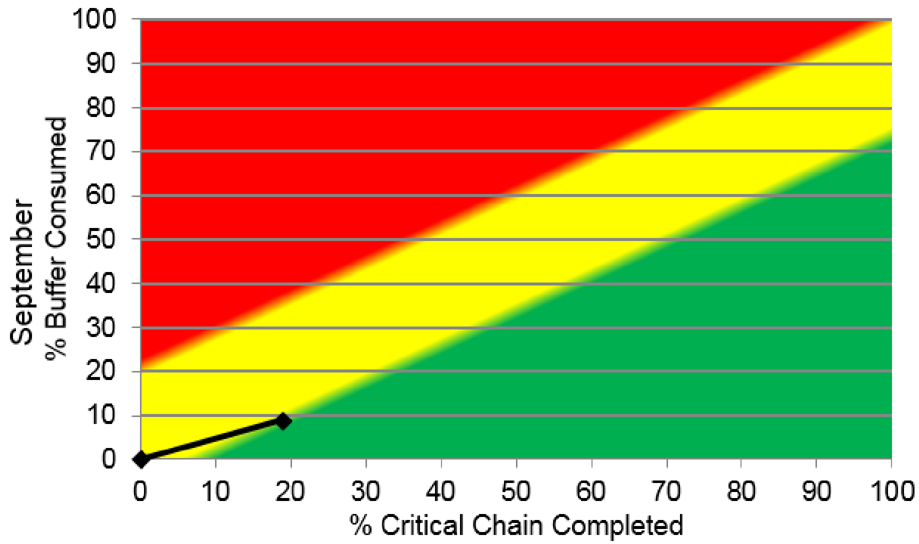
Appendix 11: Detailed Example of a Fictive Case

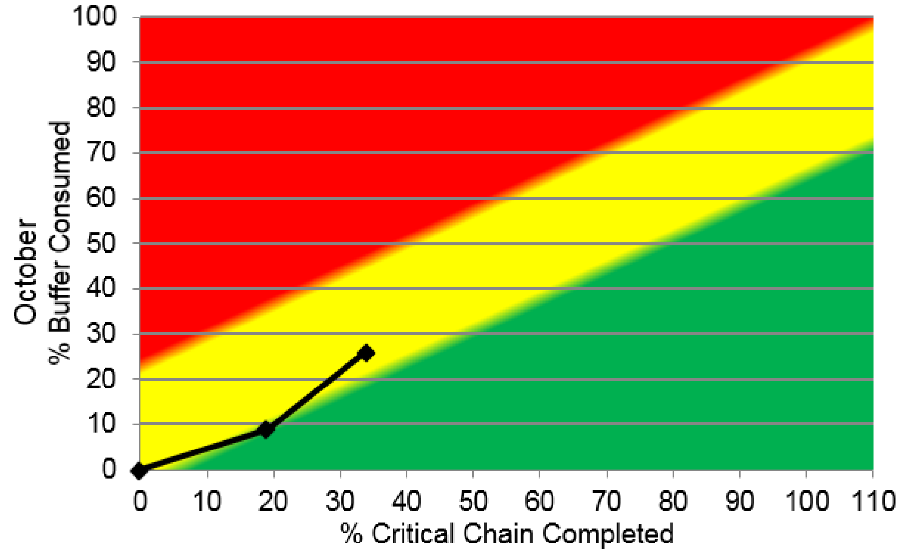
ID	Task Name	Duration	Start	Finish	Predecessors
1	**Traditional Schedule**				
2	Task A: Transport to the yard and docking	13 days	Fri 23-6-17	Tue 11-7-17	
3	Task B: Inspection of equipment	27 days	Wed 12-7-17	Thu 17-8-17	2
4	Task C: Provide access to corroded hull	14 days	Wed 12-7-17	Mon 31-7-17	2
5	Task D: Removal of old steel	6 days	Tue 1-8-17	Tue 8-8-17	4
6	Task E: Removal of old equipment	34 days	Fri 18-8-17	Wed 4-10-17	3
7	Task F: Placing new steel	21 days	Wed 9-8-17	Wed 6-9-17	5
8	Task G: Checking if equipment is suitable for remanufacturing	7 days	Thu 5-10-17	Fri 13-10-17	6
9	<Free Float for start task H>	11 days	Thu 5-10-17	Thu 19-10-17	6
10	Milestone for Start of Task H	0 days	Fri 20-10-17	Fri 20-10-17	
11	Task H: Placing and installing new equipment	43 days	Fri 20-10-17	Tue 19-12-17	6;9;10
12	Task I: Painting scope (complete hull)	28 days	Thu 7-9-17	Mon 16-10-17	7
13	Task J: Testing and comissioning	14 days	Wed 20-12-17	Mon 8-1-18	11;12
14	Contract delivery to the client	0 days	Tue 9-1-18	Tue 9-1-18	13
15					
16	**Change 1: 1 endpoint**				
17	Task A: Transport to the yard and docking	13 days	Fri 23-6-17	Tue 11-7-17	
18	Task B: Inspection of equipment	27 days	Wed 12-7-17	Thu 17-8-17	17
19	Task C: Provide access to corroded hull	14 days	Wed 12-7-17	Mon 31-7-17	17
20	Task D: Removal of old steel	6 days	Tue 1-8-17	Tue 8-8-17	19
21	Task E: Removal of old equipment	34 days	Fri 18-8-17	Wed 4-10-17	18
22	Task F: Placing new steel	21 days	Wed 9-8-17	Wed 6-9-17	20
23	Task G: Checking if equipment is suitable for remanufacturing	7 days	Thu 5-10-17	Fri 13-10-17	21
24	<Free Float for start task H>	11 days	Thu 5-10-17	Thu 19-10-17	21
25	Milestone for Start of Task H	0 days	Fri 20-10-17	Fri 20-10-17	
26	Task H: Placing and installing new equipment	43 days	Fri 20-10-17	Tue 19-12-17	21;24;25
27	Task I: Painting scope (complete hull)	28 days	Thu 7-9-17	Mon 16-10-17	22
28	Task J: Testing and comissioning	14 days	Wed 20-12-17	Mon 8-1-18	26;27;23
29	Contract delivery to the client	0 days	Tue 9-1-18	Tue 9-1-18	28
30					
31	**Change 2: Del mile+free float**				
32	Task A: Transport to the yard and docking	13 days	Fri 23-6-17	Tue 11-7-17	
33	Task B: Inspection of equipment	27 days	Wed 12-7-17	Thu 17-8-17	32
34	Task C: Provide access to corroded hull	14 days	Wed 12-7-17	Mon 31-7-17	32
35	Task D: Removal of old steel	6 days	Tue 1-8-17	Tue 8-8-17	34
36	Task E: Removal of old equipment	34 days	Fri 18-8-17	Wed 4-10-17	33
37	Task F: Placing new steel	21 days	Wed 9-8-17	Wed 6-9-17	35
38	Task G: Checking if equipment is suitable for remanufacturing	7 days	Thu 5-10-17	Fri 13-10-17	36
39	Task H: Placing and installing new equipment	43 days	Fri 20-10-17	Tue 19-12-17	36
40	Task I: Painting scope (complete hull)	28 days	Thu 7-9-17	Mon 16-10-17	37
41	Task J: Testing and comissioning	14 days	Wed 20-12-17	Mon 8-1-18	39;40;38
42	Contract delivery to the client	0 days	Tue 9-1-18	Tue 9-1-18	41
43					
44	**Change 3: Make critical path critical again and respect other links**				
45	Task A: Transport to the yard and docking	13 days	Mon 10-7-17	Wed 26-7-17	
46	Task B: Inspection of equipment	27 days	Thu 27-7-17	Fri 1-9-17	45
47	Task C: Provide access to corroded hull	14 days	Thu 27-7-17	Tue 15-8-17	45
48	Task D: Removal of old steel	6 days	Wed 16-8-17	Wed 23-8-17	47
49	Task E: Removal of old equipment	34 days	Mon 4-9-17	Thu 19-10-17	46
50	Task F: Placing new steel	21 days	Thu 24-8-17	Thu 21-9-17	48
51	Task G: Checking if equipment is suitable for remanufacturing	7 days	Fri 20-10-17	Mon 30-10-17	49
52	Task H: Placing and installing new equipment	43 days	Fri 20-10-17	Tue 19-12-17	49
53	Task I: Painting scope (complete hull)	28 days	Fri 22-9-17	Tue 31-10-17	50
54	Task J: Testing and comissioning	14 days	Wed 20-12-17	Mon 8-1-18	51;52;53
55	Contract delivery to the client	0 days	Tue 9-1-18	Tue 9-1-18	54
56					
57	**Change 4: Early -> Late start**				
58	Task A: Transport to the yard and docking	13 days	Mon 10-7-17	Wed 26-7-17	
59	Task B: Inspection of equipment	27 days	Thu 27-7-17	Fri 1-9-17	58
60	Task C: Provide access to corroded hull	14 days	Thu 14-9-17	Tue 3-10-17	58
61	Task D: Removal of old steel	6 days	Wed 4-10-17	Wed 11-10-17	60
62	Task E: Removal of old equipment	34 days	Mon 4-9-17	Thu 19-10-17	59
63	Task F: Placing new steel	21 days	Thu 12-10-17	Thu 9-11-17	61
64	Task G: Checking if equipment is suitable for remanufacturing	7 days	Mon 11-12-17	Tue 19-12-17	62
65	Task H: Placing and installing new equipment	43 days	Fri 20-10-17	Tue 19-12-17	62
66	Task I: Painting scope (complete hull)	28 days	Fri 10-11-17	Tue 19-12-17	63
67	Task J: Testing and comissioning	14 days	Wed 20-12-17	Mon 8-1-18	64;65;66
68	Contract delivery to the client	0 days	Tue 9-1-18	Tue 9-1-18	67
69					
70	**Change 5: Fill in Focus dur and push back**				
71	Task A: Transport to the yard and docking	10 days	Mon 21-8-17	Fri 1-9-17	
72	Task B: Inspection of equipment	21 days	Mon 4-9-17	Mon 2-10-17	71
73	Task C: Provide access to corroded hull	11 days	Tue 10-10-17	Tue 24-10-17	71
74	Task D: Removal of old steel	5 days	Wed 25-10-17	Tue 31-10-17	73
75	Task E: Removal of old equipment	26 days	Tue 3-10-17	Tue 7-11-17	72
76	Task F: Placing new steel	16 days	Wed 1-11-17	Wed 22-11-17	74
77	Task G: Checking if equipment is suitable for remanufacturing	5 days	Mon 18-12-17	Fri 22-12-17	75
78	Task H: Placing and installing new equipment	33 days	Wed 8-11-17	Fri 22-12-17	75
79	Task I: Painting scope (complete hull)	22 days	Thu 23-11-17	Fri 22-12-17	76
80	Task J: Testing and comissioning	11 days	Mon 25-12-17	Mon 8-1-18	77;78;79
81	Contract delivery to the client	0 days	Tue 9-1-18	Tue 9-1-18	80
82					
83	**Change 6: Insert PB (=RCCPM Schedule)**				
84	Task A: Transport to the yard and docking	10 days	Tue 1-8-17	Mon 14-8-17	
85	Task B: Inspection of equipment	21 days	Tue 15-8-17	Tue 12-9-17	84
86	Task C: Provide access to corroded hull	11 days	Tue 19-9-17	Tue 3-10-17	84
87	Task D: Removal of old steel	5 days	Wed 4-10-17	Tue 10-10-17	86
88	Task E: Removal of old equipment	26 days	Wed 13-9-17	Wed 18-10-17	85
89	Task F: Placing new steel	16 days	Wed 11-10-17	Wed 1-11-17	87
90	Task G: Checking if equipment is suitable for remanufacturing	5 days	Mon 27-11-17	Fri 1-12-17	88
91	Task H: Placing and installing new equipment	33 days	Thu 19-10-17	Mon 4-12-17	88
92	Task I: Painting scope (complete hull)	22 days	Thu 2-11-17	Fri 1-12-17	89
93	Task J: Testing and comissioning	11 days	Mon 4-12-17	Mon 18-12-17	90;91;92
94	<Project Buffer>	15 days	Tue 19-12-17	Mon 8-1-18	93
95	Contract delivery to the client	0 days	Tue 9-1-18	Tue 9-1-18	94

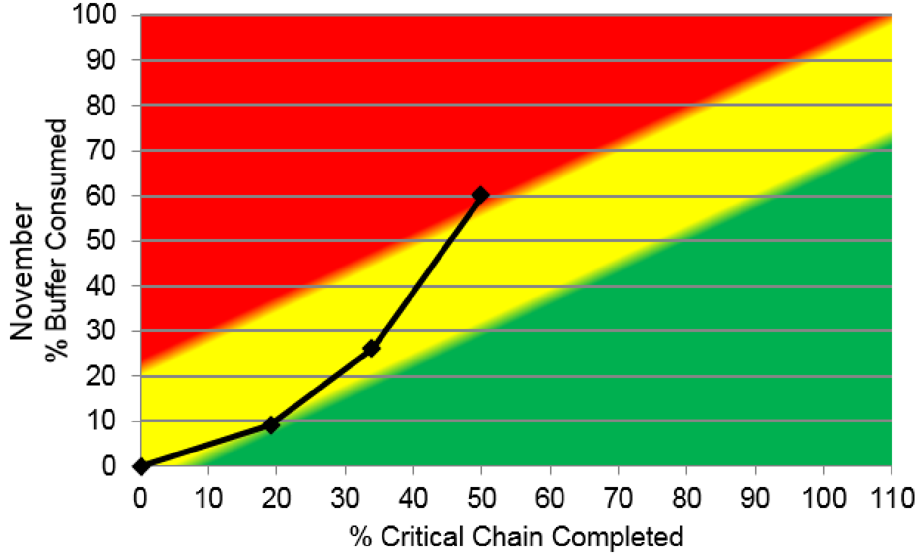


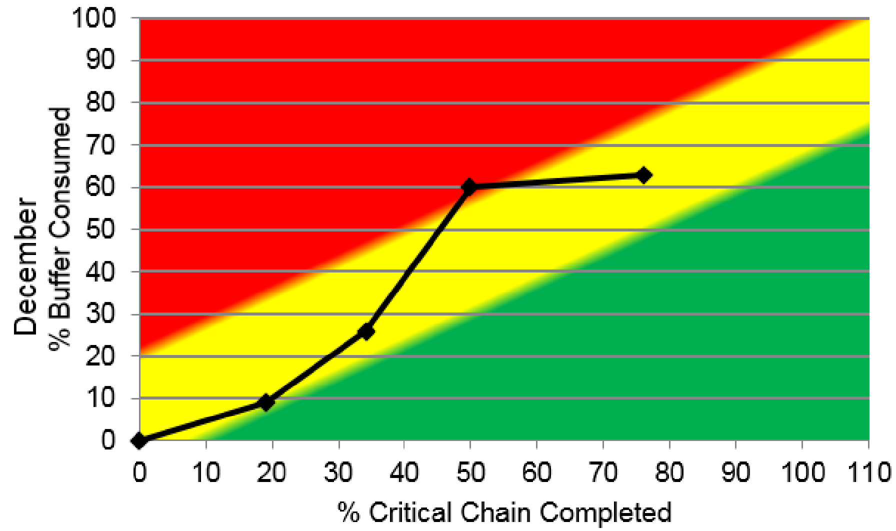
Project: Example schedule chan
Date: Wed 19-7-17

Task	Project Summary	Manual Task	Start-only	Deadline	Manual Progress				
Split	Inactive Task	Duration-only	Finish-only	Critical	Slack				
Milestone	Inactive Milestone	Manual Summary Rollup	External Tasks	Critical Split					
Summary	Inactive Summary	Manual Summary	External Milestone	Progress					

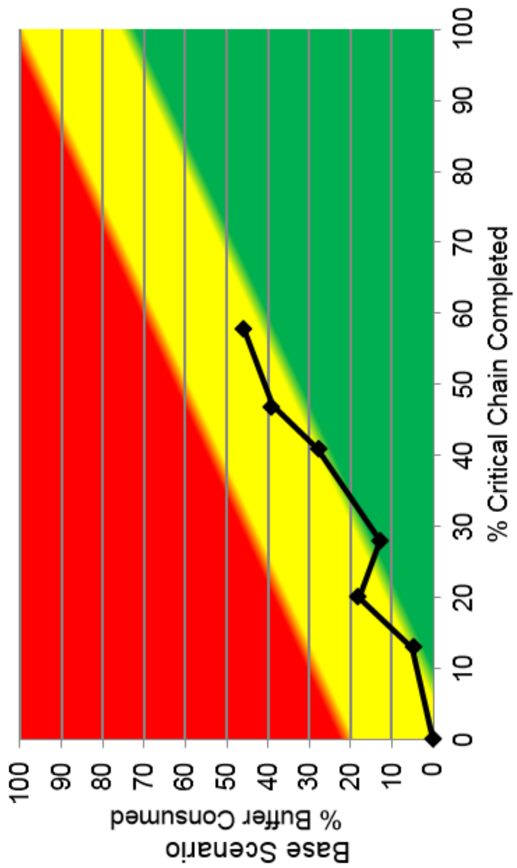

September
% Buffer Consumed
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
% Critical Chain Completed

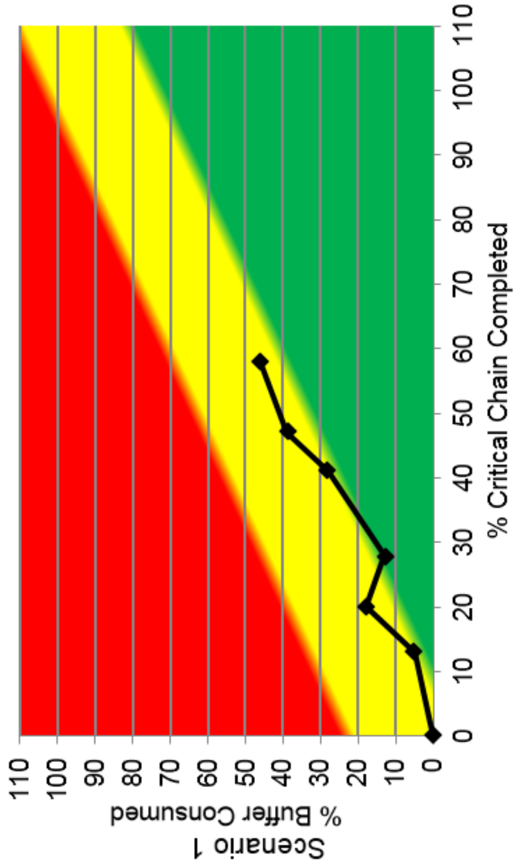

October
% Buffer Consumed
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
110
% Critical Chain Completed

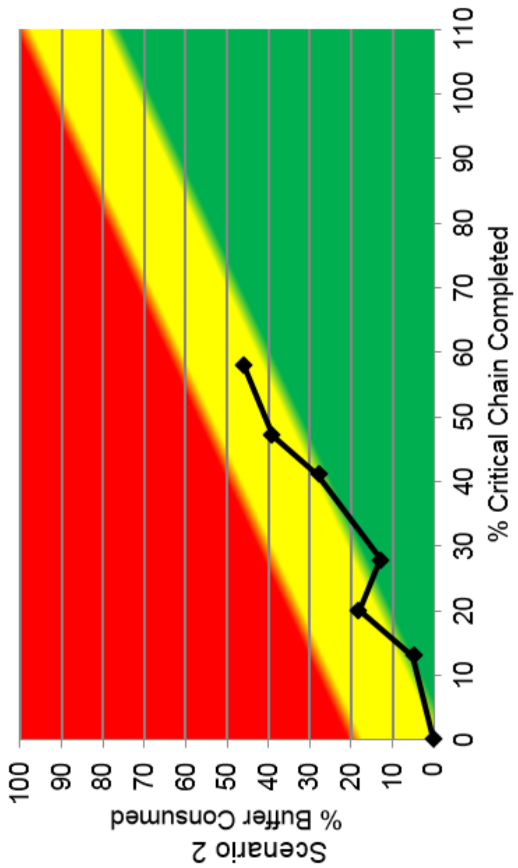

November
% Buffer Consumed
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
110
% Critical Chain Completed

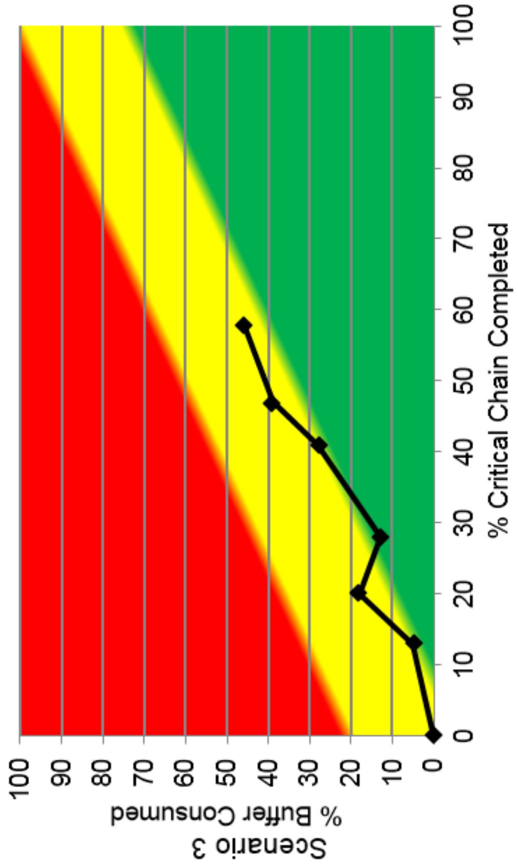

December
% Buffer Consumed
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
110
% Critical Chain Completed

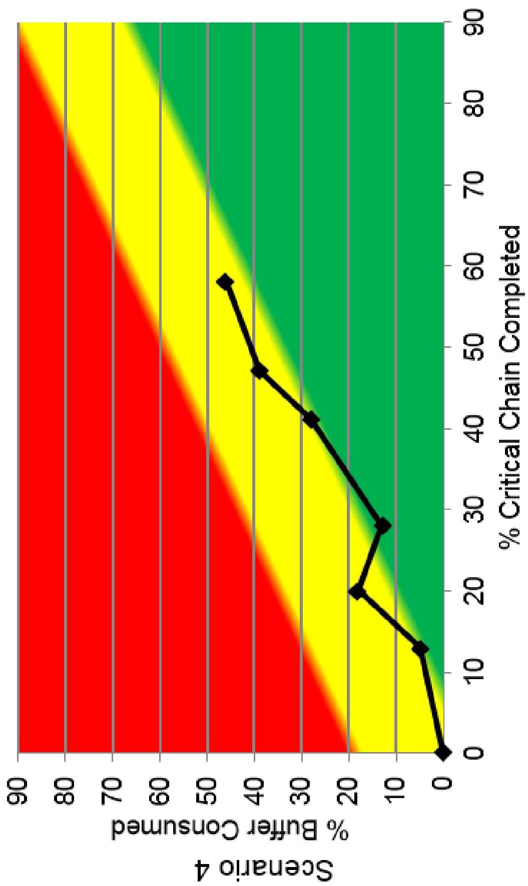
Appendix 12: Fever Chart Dynamics

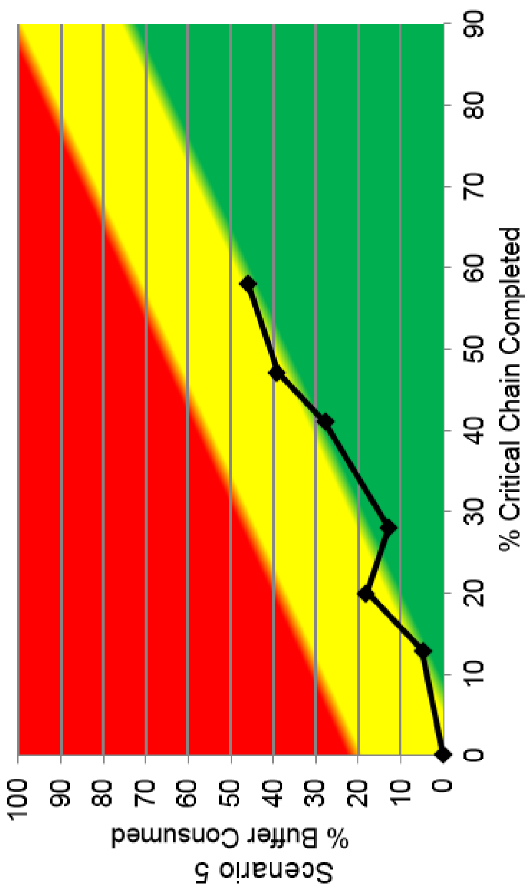


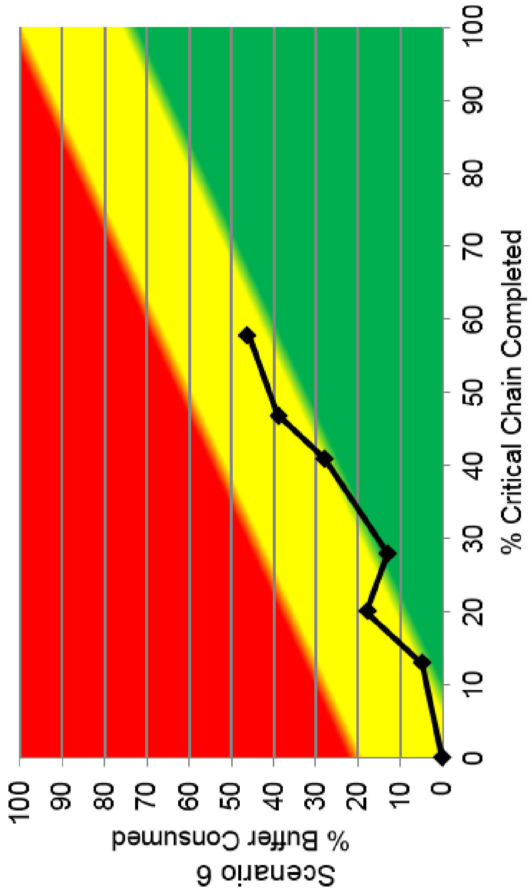


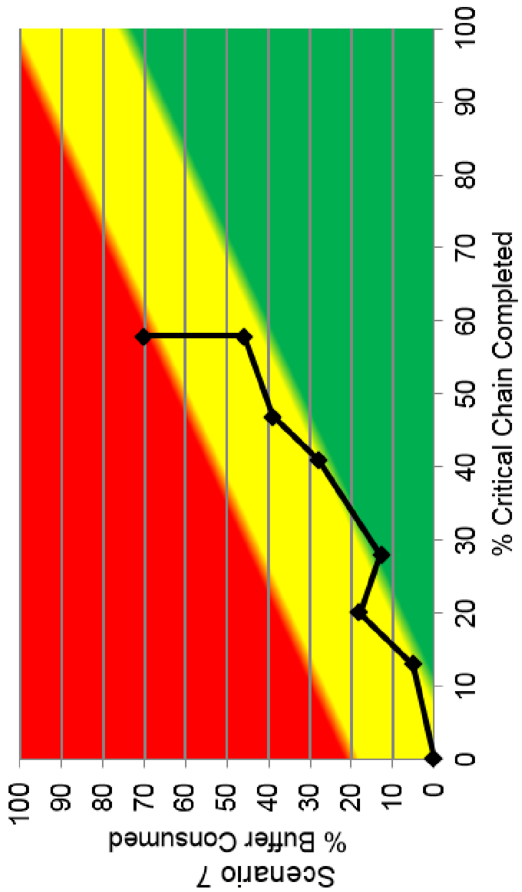


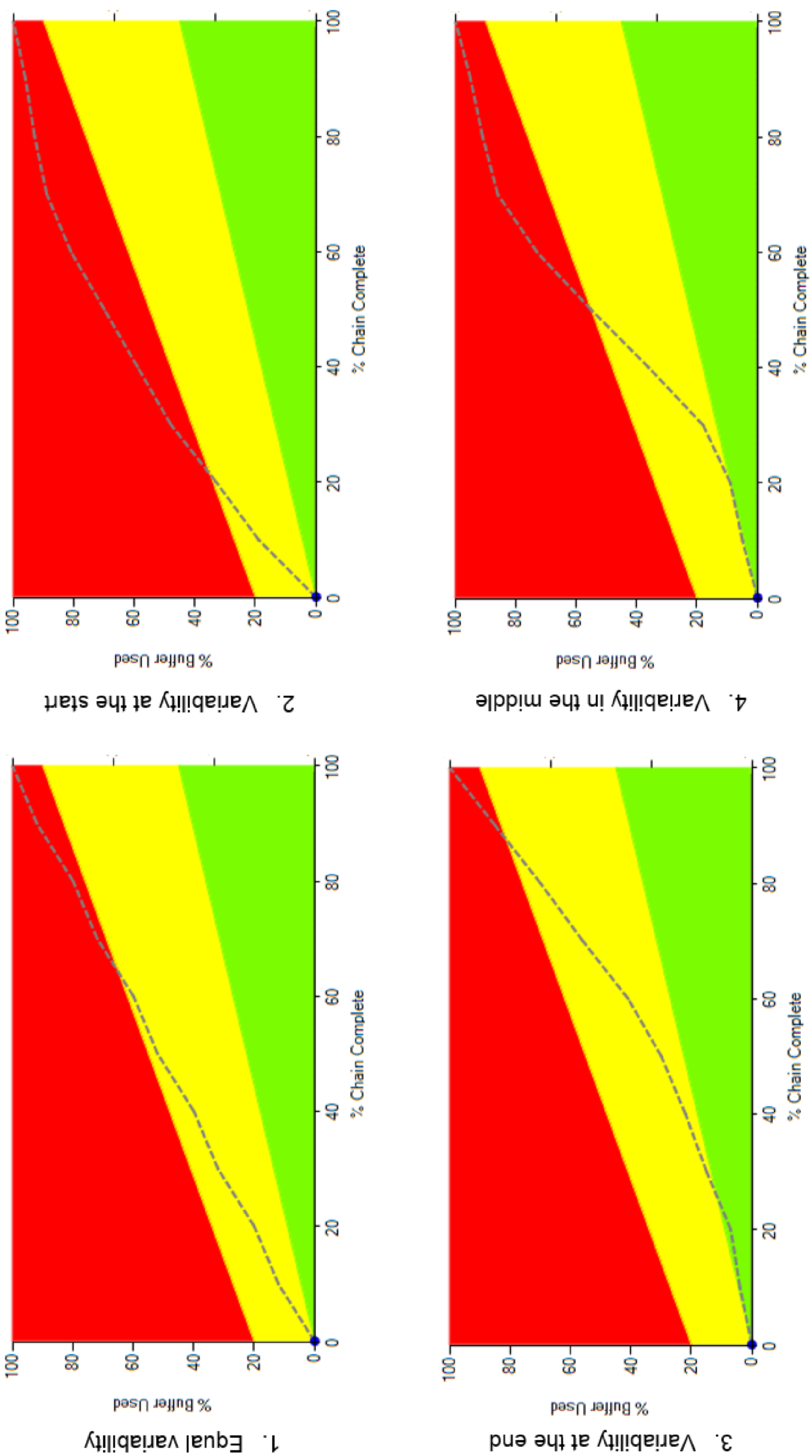



Scenario 4
% Buffer Consumed
% Critical Chain Completed
0
10
20
30
40
50
60
70
80
90


Scenario 5
% Buffer Consumed
% Critical Chain Completed
0
10
20
30
40
50
60
70
80
90
100


Scenario 6
% Buffer Consumed
% Critical Chain Completed
0
10
20
30
40
50
60
70
80
90
100


Scenario 7
% Buffer Consumed
% Critical Chain Completed
0
10
20
30
40
50
60
70
80
90
100



1. Equal variability

2. Variability at the start

3. Variability at the end

4. Variability in the middle

Appendix 13: Progress Reporting Questionnaire

Questionnaire to help in the qualitative validation of an alternative method (RCCPM) for project progress reporting in the maritime and offshore industry

- When answering the questions, imagine you are a project manager at a shipyard.
- You have 2 progress reports; “Type A” and “Type B”. Use these to answer questions 5-11.
- There are 11 questions.
- You don’t have to fill in your name/student number; you are anonymous.
- The questionnaire should take you 10-15 minutes.
- Please also hand in the progress reports.
- You can share any additional comments in the comment box at the end or send me an email (bjornvanbouwelen@gmail.com).

General questions (you don’t need the progress reports yet)

1. I am a master (or exchange) student Marine Technology at TU Delft.
   - ☐ True
   - ☐ False, …………………………………………………………………….(please explain)

2. I have at least basic knowledge about project management (such as earned value, WBS and critical path).
   - ☐ True
   - ☐ False

3. To reduce the lead time (duration) of a project you should:
   - ☐ Encourage multitasking
   - ☐ Eliminate multitasking
   - ☐ Makes no difference

4. To reduce the lead time (duration) of a project you should:
   - ☐ Start each task as early as possible
   - ☐ Start each task as late as possible
   - ☐ Makes no difference

Questions about the progress reports

5. Please rank the (7) elements of the progress reports in the order of usefulness (1 is most useful). If you believe an element is not useful at all, then do not give it a rank. A short explanation of each element is given at page 4.

Element	Ranking
Earned value chart	
Histogram	
Baton task	
Fever chart	
3 most crucial tasks	
3 most critical risks	
Date based chart	

6. What piece of information would you prefer when making a decision as a project manager:
   - ☐ The estimated % of (physical) completion of each activity (like 40% complete)
   - ☐ The estimated number of days needed to complete each activity (like 10 days remaining)
   - ☐ No preference

   Explanation (not mandatory):

   ____

   ____

7. Do you understand how to interpret an earned value chart (S-curve)?
   - ☐ Yes, completely
   - ☐ Yes, but not completely
   - ☐ No

   Explanation (not mandatory):

   ____

   ____

8. Do you understand how to interpret a fever chart?
   - ☐ Yes, completely
   - ☐ Yes, but not completely
   - ☐ No

   Explanation (not mandatory):

   ____

   ____

9. The three coloured (traffic light) system of the fever chart provides better info on when to perform control (mitigation) actions compared to the earned value chart.
   - ☐ True
   - ☐ False

   Explanation (not mandatory):

   ____

   ____

10. Please assess the 2 progress reports on the list of criteria below.
    1. First review the criteria and add one (or more) if you miss something.
    2. Rank the criteria in the order of importance (1 is the most important). If you believe a criterion is not important at all, then do not give it a rank.
    3. For each criterion, check the box of the progress report you think is the best. Alternatively, you can opt to say that there is no difference or that they are equally good.

Criterion Which progress report …	**Ranking**	**Type A**	**Type B**	**No difference / Equal**
… gives you the most information to make a decision for the upcoming week of the project?		☐	☐	☐
… gives you the best information to make a decision for the upcoming week of the project?		☐	☐	☐
… gives you the quickest overview/takes the least time to understand?		☐	☐	☐
… provides more clarity about the status of the project?		☐	☐	☐
… provides you the best focus?		☐	☐	☐
… provides you the clearest priorities?		☐	☐	☐
… would be the most helpful to get the project back on track?		☐	☐	☐
…		☐	☐	☐
…		☐	☐	☐

11. Next week you will receive only 1 progress report. You're the project manager, so you can decide which one it will be. Do you have a preference?
    - ☐ Yes, Type A
    - ☐ Yes, Type B
    - ☐ No preference

    Please explain your answer to question 11 as clear and as elaborated as you can:

    ____

    ____

    ____

Comment box

Short explanation of the elements in the "Type A" progress report

- Earned value (S-curve) chart: showing the cumulative % of each week (both in a chart and a data table underneath) of
  - Planned value (PV) (black): the amount of work in the baseline planning.
  - Earned value (EV) (red): the amount of work that is achieved.
  - Estimate to complete (ETC) (green): the estimated amount of remaining work that is needed to complete the project.
- Histogram: showing the % of the specified week only (both in a chart and a data table underneath) for the same 3 elements of the earned value chart.

Short explanation of the elements in the "Type B" progress report

- Buffer used: the amount of buffer used. Buffer is used if an activity on the critical chain uses more time than the focus (mean) duration. The size of the buffer is based on the difference between the focus and low-risk duration of all activities that lie on the critical chain.
- Chain complete: the progress on the critical chain.
- RBCI (Relative Buffer Consumption Index): buffer used/chain complete. An index that indicates the expected amount of buffer usage (i.e. 0.5 means that half of the buffer will be used if the project continues as it did until now).
- Baton task: the next task on the critical chain, "the next runner in the relay race". The ones involved in that task should fully prepare themselves and receive all input needed to start as soon as the predecessor is finished.
- Fever chart: the green/yellow/red chart showing the % buffer used and the % chain complete.
  - Variability profile: the dashed grey line in the fever chart; the amount of buffer we expect to consume when we are at a given % chain complete, based on the variability (difference between the focus and low-risk durations).
  - Colour
    - Green: No action is needed; the project is expected to finish ahead of schedule.
    - Yellow: Analyse the cause(s) of the buffer use and set-up a mitigation plan.
    - Red: Execute the plan.
- 3 most crucial tasks: a delay in these tasks has the most effect on a delay of the entire project (based on Monte Carlo simulation). Only tasks that take place between the current and next status date can be displayed here.
- 3 most critical risks: if these risks occur, then the project will be delayed the most (based on Monte Carlo simulation). Only tasks that take place between the current and next status date can be displayed here.
- Date based chart: the chart at the bottom showing the course of RBCI, buffer used and chain complete, with a data table underneath showing those 3 elements for all progress reports until now.

Appendix 14: Comments on the Progress Reporting Questionnaire

Those who prefer traditional (A) said:
• "Prefer A, although I like the level of detail of A to determine direction of actions. B is easier to determine if action is needed." • "Type A is more familiar and gives a better overview of the expected progress of the project." • "Although I really much like the representation in B; I would rather spend extra time on figuring out from A the status of my buffer AND know about the EV. So I'd love to have both :)" • "A says more about what the project is doing now. B is useful for finding crucial tasks, but these might change." • "A provides clearer and more familiar information."
Those who prefer RCCPM (B) said:
• "B is easier and has more practical information." • "It takes time to understand and go through the report, but you can get more useful information out of it." • "I think report B is easier to read." • "I like the fact that type B shows the buffer used and how many days remain." • "More information and also shows some crucial tasks. For type A the main conclusion is 'work harder'. Missing made cost (AC) in type A."
Those who had no preference said:
• "With type A I have a better impression of the history of the project. With type B I have better information to get ready for the next week." • "Both have advantages. It depends on personal preference. I lean to A, because I am more familiar with it."