RESOURCE BUFFERS IN CRITICAL CHAIN PROJECT MANAGEMENT

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LIST OF ABBREVIATIONS

C	Critical chain activities
CC	Critical Chain
CCPM	Critical Chain Project Management
CI	Complexity index
CPM	Critical Path Method
C&PM	Cut and Paste Method
FB	Feeding Buffer
NC	Non-Critical activities in CCPM
OS	Order Strength
PERT	Programme Evaluation and Review Technique
PB	Project Buffer
PSPLIB	Project Scheduling Problem Library
RB	Resource Buffer
RC	Resource Constrainedness
RF	Resource Factor
RS	Resource Strength
RSSM	Root Square Error Method

RU	Resource Use
SSQ	Square root of the sum of SQuares method
TOC	Theory of Constraints

NOMENCLATURE

A_i	shortened estimate of activity *n* duration
a_k	total availability of renewable resource type k
d	duration of an activity
K	number of resource types
m	most likely duration in PERT
μ	mean
n	number of activities
o	optimistic duration in PERT
p	pessimistic duration in PERT
r_{ik}	amount of resource type k require by activity i
$\bar{r}_k$	average quantity of resource type k
σ	standard deviation
S_n	safe estimate of activity *n* duration
T	the expected activity duration in PERT

ABSTRACT

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Resource Buffers in Critical Chain Project Management

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Critical Chain Project Management (CCPM) is a relatively new method of scheduling. Whilst it has a number of advantages over traditional scheduling methods, it is still far from perfect. A literature review of the CCPM method, its shortcomings and suggestions for improvement is presented in this thesis. The review reveals that, in addition to other issues addressed, most researchers concentrate on the question of project and feeding buffer size. Issues concerning the resource buffer are ignored in the literature. This is a crucial gap in research, as resources are needed to perform tasks, and resource buffers protect the critical activities from the unavailability of resources. Although the original CCPM method treats resource buffers only as a notice or a 'wake-up call', the research in this thesis proposes to include resource buffers as time buffers with the assigned resources and cost.

The research in this thesis provides a simulation methodology to answer the problem of resource buffer allocation and sizing. The simulation is performed on 3 projects, generated by RanGen software, each with the same characteristics of network order strength, resource strength and resource use. Three different buffer sizes and three different uncertainty levels are applied to the schedules. The analysis of simulation results demonstrates that no optimum resource buffer can be obtained for all projects in general. Each project, even with the same characteristics, behaves differently. Therefore the simulation methodology, developed and presented in the thesis, has to be applied to decide on the size of resource buffer in a specific project. The research outcomes demonstrate that resource buffers cannot be neglected and should be simulated using CCPM schedules, as they help to reduce the total project duration during execution. The decision whether to apply the resource buffer should also be based on financial analysis of the cost and benefits of inclusion.

DECLARATION

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CHAPTER 1. INTRODUCTION

1.1. Problem statement

Due to the rapidly changing complex environment, more and more companies implement their strategy through projects (Winter et al. 2006). Once only applicable to construction, defence, and research and development sectors, projects are now being performed in a wide range of fields, including information technologies, banking, etc. As stated by Winter et al. (2006), project management is the most popular model to implement changes or improvements in business and its strategy, to create new products. The rising importance of project management is also demonstrated by the increasing number of certified project managers. According to data from PMI Today (2009), the number of PMI certified project management professionals increased by more than 1000 per cent during the 1999-2009 decade, from 27052 to over 330000 people.

Recognition of the importance of project management has led to a high number of research publications. Unfortunately, despite the extensive research performed in the field of project management, the percentage of unsuccessful projects across different sectors is still high (Yeo and Ning 2002; Flyvbjerg 2003; Blackstone et al. 2009; The Standish Group 2013). The question of what makes a project successful or unsuccessful is a separate topic, and has been analysed by a number of researchers. The question of how to measure the success of a project remains. Is a late project with cost overrun unsuccessful, even if it generates higher income than planned later on? Is a project where a building is constructed on time and within budget successful, even if it is not used afterwards? Researchers analyse different project success measures. For example, Patanakul et al. (2010) categorize project success dimensions into internal, customer-related and organisational-related. These include not only cost, time, and performance, but also customer satisfaction, actual utilisation and benefits, financial, market, and organisational benefits. Rashvand and Zaimi (2014) discuss the satisfaction of clients and stakeholders as the measures of project success. However, in general cases it is widely accepted that a successful project is finished within the time, cost and specifications planned (Cao and Hoffman 2011). Rashvand and Zaimi (2014) call these success measures 'traditional.' The Standish Group (2013) also describe a successful project as being delivered on time, on budget, and with required features and functions.

The often cited cases of failed projects have excited the curiosity of scientists and practitioners and lead to discussions on the reasons why projects are not successful. Belassi and Tukel (1996) provide a useful overview and classification of crucial success factors. They state that the factors relate to the project itself (the size and value, the uniqueness of project activities, density of a project, life cycle, and urgency), to the project managers (their ability to delegate authority, trade-off, coordination, the perception of his/her role and responsibilities, competence, commitment), to the team members (technical background, communication skills, trouble shooting, commitment), to the organization (top management support, project organizational structure, functional managers' support, project champion), and to the external environment (political, economic, social, technological environment, nature, client, competitors, sub-contractors) (Belassi and Tukel 1996).

Many researchers believe that factors related to scheduling are crucial for successful project implementation. They cite the accuracy of a baseline schedule

(Dursun and Stoy 2011) or inadequate scheduling (Assaf and Al-Hejji 2006) as one of the most critical success factors. Rand (2000) claims that uncertainty is the underlying cause of schedule overruns. Pinto and Mantel (1990) demonstrate with empirical investigations that the adequate planning for uncertainty and corrective actions is the most important element for the successful implementation of a project.

The traditional scheduling methods are Critical Path (CPM), and Programme Evaluation and Review Technique (PERT). Unfortunately, these methods are still far from perfect (more information in Chapter 2.2). Acknowledgement of their shortcomings led to creation of a new Critical Chain Project Management (CCPM) technique. CCPM was introduced by E. Goldratt in his bestselling novel *Critical Chain* (1997).

The term ‘critical chain’ means the longest chain of activities that satisfies both the precedence and the resource availability requirements. The main idea of CCPM is to remove the safety time from the durations of separate activities and aggregate it into strategically allocated project, feeding, and resource buffers. Project buffer protects the end date of a project from delays; feeding buffers enable to take advantage of the early finishes of activities and protect the critical chain from delays in non-critical chains, while resource buffers ensure the required resource availability when needed. The technique of CCPM is discussed in more detail in Chapter 2.

From the very beginning the interest in CCPM was huge among both practitioners and researchers. Practitioners were giving examples of successful implementations of projects under CCPM (for examples see www.realization.com), software developers started creating and selling commercial software for CCPM (for example, Agile CC, Aurora CCPM, Being Management 2, cc-MPulse, CCPM+, Concerto, Lynx, ProChain, PSNext), and the discussion groups were intensely used (www.prochain.com/discussion.html, yahoo discussion groups, linked-in and etc.). A few books have also been written on the subject (Goldratt 1997; Newbold 1998; Leach 1999; Woeppel 2006; Newbold 2008; Newbold 2014).

Meanwhile, researchers raised a number of questions about CCPM, including the novelty of CCPM, and the validity of the assumptions on which CCPM is based. The researchers proposed solutions to the identified CCPM shortcomings, and a review of these is presented in Chapter 2 of this thesis. The majority of these research publications addressed the question of how to size the project and feeding buffers. However, the research so far completely ignores the analysis of resource buffers. Goldratt (1997) introduced resource buffers as a ‘wake-up call’, used to warn a resource to be ready for critically important work when needed. The ‘wake-up call’ might work for human resources that are able to switch from one task to another. Unfortunately, it might not work for other resources, for example materials or equipment, which cannot be easily moved from another unfinished activity, bought just when needed or at short notice. Even human resources might not be available if the ‘wake-up call’ is too late. Therefore, not only alert, but idle time in the form of a resource buffer can be beneficial. The idle time for the resources on a critical chain would ensure their availability when needed, in this way increasing the chances of finishing the project on time or ahead of schedule. On the other hand, resource buffers might keep resources idle and increase the cost of a project. Nevertheless, the benefits gained from the timely or early completion of a project might be higher than the costs of resource buffers. It is important to use the smallest possible size of resource buffer, which would help to shorten the project duration.

Surprisingly, the importance of resource availability for successful project implementation in CCPM has been neglected. There are no articles on the issue of resource buffers, neither as a 'wake-up call' nor as idle time in CCPM. No information is available on how to size and where to place the resource buffer. Moreover, some of the newest publications on CCPM (for example, Truc et al. 2012; Peng and Huang 2013; Ma and Jiang 2012) do not include resource buffers in their description of the CCPM technique. Practitioners omit these issues as well: currently no commercial CCPM software includes resource buffers; they concentrate on the feeding and project buffers only. The tendency to exclude resource buffers from the CCPM schedules is unjustified. The question of how big the resource buffer should be, and where it should be located, needs to be investigated.

The use of resource buffers would protect the critical chain from resource unavailability. In cases where some of the critical chain activities are finished earlier than planned, resource buffers would also ensure that the proceeding critical activities could start earlier than planned, as the required resources would be ready for work. The protected critical chain and the possibility of taking advantage of early finishes in critical activities would help to finish the project on time, or ahead of schedule.

The problems identified with resource buffer usage, sizing and allocation are analysed in this thesis. The research aims and objectives are presented in the following Chapter 1.2.

1.2. Research aim and objectives

This thesis aims to provide a systematic method for the use of resource buffers in Critical Chain Project Management.

To achieve the aim, the following research objectives were identified:

1. To review previous research on Critical Chain Project Management and the use of resource buffers in particular. What are the shortcomings of traditional project management planning techniques? Does Critical Chain Project Management technique have advantage over traditional project management planning techniques? What are the shortcomings of CCPM? What is the current state of research knowledge on CCPM? What are the main issues analysed by CCPM researchers? What further research should still be done on CCPM? What research gap could the thesis address? What methodology is suitable to achieve the aim of this thesis?
2. To develop a simulation method to test the usefulness of resource buffers in CCPM projects under different uncertainty levels. Where should the resource buffer be placed? How can the project implementation be simulated? What are the simulation performance measures? The created simulation algorithm has to be applied for the projects under low, medium and high uncertainty levels.
3. To examine the issue of resource buffer cost. Is it worth using resource buffers in CCPM projects in terms of profit? Or do they cost too much, and schedules without resource buffers are more appropriate?

4. To determine the optimal size of the resource buffer for all projects. Does an optimal size of resource buffer exist for all projects? How can it be expressed?

1.3. Scope

The scope of this thesis is limited to resource buffers in Critical Chain Project Management in a single project environment. There is no attempt to address multi-project environment.

An assumption has been made that the activities are independent and cannot be split. It has also been assumed that resources are limited. This is because in the case of unlimited or immediately available resources, the resource buffers are not necessary, and the results of this thesis are not relevant.

It is also important to mention that this research does not intend to provide an exact solution for the resource buffer usage. It does not replace human judgement, experience and qualitative factors influencing the decisions made regarding the use of resource buffers. The developed simulation algorithm acts as a decision support tool, providing the decision maker with the quantitative information of possible project outcomes.

1.4. Thesis outline

The thesis includes 6 chapters, which are described below:

Chapter 1. Introduction

This chapter describes the importance of project management and CCPM in particular. The gap in CCPM research is revealed, the research aim and objectives are presented, and a brief introduction to the thesis contribution to knowledge is provided.

Chapter 2. Literature review

Chapter 2 provides a literature review on traditional project management techniques and CCPM. Chapter 2.2 gives a short review of scheduling techniques used in traditional project management: the concept, advantages, disadvantages and need for improvement. Traditional project management methods are followed by the fundamental principles of CCPM in Chapter 2.3: the terminology, origin, steps, main features and benefits. Chapter 2.4 provides a literature review of research on CCPM, the proposals of other researchers to improve CCPM, and questions regarding CCPM that still need further research. Finally, a more detailed review is presented on the question of resource buffers in Chapter 2.5.

Chapter 3. Methodology

The methodology section provides the strategy of procedures applied to achieve the raised research objectives. First of all, the objective function, hypotheses and simulation performance measures are defined. This is followed by a description of how the baseline project is created, i.e. how the feeding and project buffers are sized. Next, a detailed explanation is given for reasons why a certain project scheduling problem set has been chosen, and the specific input parameters for schedule generation are defined. The Chapter 3.3.6 presents the independent variable parameters, which are entered into the simulation model. This is followed by Chapter 3.3.7 – a detailed explanation of how the project execution is simulated, i.e. how the random durations of activities are generated and how updates to the schedule during execution are made. Next, the selection of simulation software is described. The other software used for research, i.e. for the generation of schedules and random activity durations, is also mentioned. The simulation algorithm is presented in Chapter 3.5 and a summary of the chapter on simulation design is given in Chapter 3.6.

Chapter 4. Simulation results

Chapter 4 starts with an explanation of the analysis of simulation results: finding the suitable statistical distribution for the simulation output data, deciding on the appropriate measure of the average value, and assuring that the number of performed simulations is sufficient. Next, a check is performed to tell whether the differences between project durations are statistically significant. Two types of tests are used for this purpose, and are described in Chapter 4.1.4. This is followed by an explanation of the graphical representation of the results. The results of separate projects are analysed and a comparison of project output data is presented in Chapters 4.2-4.4.

Chapter 5. Discussion

Chapter 5 starts with a discussion of the main findings from the performed simulations. The simulation results are summarized and conclusions are made. Next, the financial issues of resource buffer application in CCPM are discussed. In Chapter 5.3-5.4, an illustrative example is presented to demonstrate the decision making process on the resource buffer size, depending on the costs of resource buffers and the profits of early finishes. Based on the financial discussion, general recommendations for resource buffer usage are given, which include proposals of whether to use resource buffers at all, and suggestions on how big resource buffers should be. Next, the validation of the research is addressed in Chapter 5.6.

Chapter 6. Conclusions, contribution to knowledge, future research

At the beginning of Chapter 6, the raised research objectives are recapped. An examination into whether the research objectives were achieved is carried out. This is followed by the conclusions, drawn from the research presented in previous chapters. Next, the research limitations are described, and, the contribution made to the field of knowledge is emphasized. The thesis ends with recommendations for future research.

CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

The objectives of the literature review were:

1. To describe the shortcomings of traditional project management planning techniques and the need of CCPM.
2. To define the terminology of CCPM.
3. To determine the benefits and shortcomings of CCPM.
4. To review the current state of research knowledge on CCPM.
5. To identify the research gap in the field of CCPM.

This chapter starts with a brief overview of traditional project management techniques, in particular the well-known Programme Evaluation and Review Technique (PERT) and Critical Path Method (CPM). The disadvantages of these methods are highlighted and the evolution of Critical Chain Project Management (CCPM) is described. Next, the terminology and main principles of CCPM are presented, together with the research already done on CCPM by other scientists, and the questions still left to be addressed. The choice to investigate resource buffers in this thesis is then justified.

2.2. Traditional project management planning techniques

The discipline of project management covers a variety of subjects, for example, risk and configuration management, planning and control, organisational structure, resource allocation, financing, etc. Among others, the topic of scheduling has been given substantial attention by researchers and practitioners. In fact, the majority of books written on the discipline of project management include a chapter on scheduling. Furthermore, research has shown (Assaf and Al-Hejji 2006) that ineffective planning and scheduling is one of the most important causes of project delay.

The purpose of scheduling is to plan the necessary activities in time and allocate the required resources in an optimum way. The schedules serve as a basis for ordering external and planning internal resources, for forecasting cash flow, for monitoring the project performance and taking corrective actions, for committing obligations to customers and making agreements with subcontractors, and for creating an accountability system.

There are a number of project management planning and scheduling techniques which are presented in project management books, and discussed and analysed in publications of scientific journals. Some examples are Critical Path Method (CPM), Programme Evaluation and Review Technique (PERT), Graphical Evaluation and Review Technique (GERT), Venture Evaluation Review Technique (VERT), Line of Balance and others. However, although promising results in an artificial research environment, GERT, VERT, and Line of Balance are not the most popular methods in a real life environment (Morris 1997). This is most likely the reason why the majority of the project scheduling research done during the last decade has focused on the improvement of the most popular methods: CPM and PERT. These two most popular methods are discussed in the following chapters.

2.2.1. Critical Path method (CPM)

The foundations for the creation of Critical Path Method lie in an industrial environment, the predecessors being the scheduling of plant maintenance and a plant overhaul, both of which involved activity sequencing elements. CPM was published formally in 1959 by DuPont and the Remington Rand Univac. Although some authors argue that CPM is not applicable in the construction industry as it focuses on duration only and neglects cost (Birrell 1980), the history of developing CPM shows it was initially inspired by the search for an optimum schedule in terms of both cost and time for a project with engineering and construction activities. It took about a decade for CPM to become the most popular method used for managing construction projects (Morris 1997) and it still continues to be the most widely applied tool at present (Liu and Kuo-Chuan 2009).

Critical path method starts by arranging activities in a logical way following the finish-to-start precedence relationship. Then the total float (slack) is calculated by forward and backward passes and the critical path is defined. Total float is the amount of time by which an activity could be delayed without postponing the end date of a project. It is a difference between the latest finish date and the earliest finish date of an activity. Activities having zero total float are defined as critical activities. The delay in a critical activity would have an impact on the total duration of a project, while non-critical activities could be delayed by the amount of a total float without affecting the end date of a project. The path consisting of critical activities is called the critical path and it is the longest path in a network.

The popularity of CPM can be explained by the following advantages: it enables calculations of trade-offs between project cost and duration, allows optimization of a schedule in terms of minimum duration, maximum net project value, minimum cost or other objective functions (Demeulemeester and Herroelen 2002); it helps monitoring a project at any point of time by observing critical path, focuses attention on the most critical activities (Lechler et al. 2005); and enables resource levelling by using resource histograms (Kliem et al. 1997).

However, despite the obvious advantages of CPM, the method has been criticised by a number of researchers. One of the first researchers who noticed the shortcomings of CPM was George S. Birrell. However, his critique on the insufficient emphasis of cost in CPM (Birrell 1980) should be considered with caution. CPM deals with the normal time (associated with the lowest cost) and the crash time (associated with the maximum resources) (Gray and Larson 2006). Extending the task duration beyond the normal time point does not save money, while employing more resources than the maximum crash point does not save time, and might even be impossible due to space and other requirements. The optimum cost/time values can be obtained in between the normal and crash points. In fact, there have been many publications dealing with the optimisation of schedules regarding time and cost (Hegazy 1999; Chassiakos and Sakellaropoulos 2005; Ammar, 2011). In this way CPM deals not only with the minimization of duration, but also with the minimization of cost.

However, there are still valid and significant shortcomings in the method, which should not be ignored. First of all, networks in large projects can become too complex, difficult to understand and communicate. Therefore Gantt charts are usually used in combination with CPM. Moreover, focus on a separate critical activity might be inappropriate, as a critical path might change over time, non-critical activities could become critical soon, and changing focus on frequently skipping critical paths instead of paying attention to the global goal of a project might not be the best decision. In addition, CPM is only suitable for a single-project environment, as it does not provide any guidelines for managing several projects simultaneously (Lechler et al. 2005). Furthermore, CPM employs the assumption of unlimited resources (Herroelen and Leus 2005a), which might not be true in a real life environment. To overcome the last disadvantage, the more advanced CPM addresses the problem of resource constrained project scheduling (RCPS). A considerable amount of research on RCPS has been performed over the years, resulting in promising solutions. However, as Herroelen (2005) states, the proposed methods are not applied in practice, and the reasons for their rejection are not completely clear. Last, but not least CPM is deterministic: it does not account for the stochastic nature of activity duration and uncertainty in a project environment (Cho 2009). In fact, "CPM underestimates the likely project duration when activity durations are uncertain" (Herroelen and Leus 2005a).

The acknowledgement of the last CPM shortcoming motivated the development of another scheduling technique: Programme Evaluation and Review Technique (PERT).

2.2.2. Programme evaluation and review technique (PERT)

At the same time as CPM, the Programme Evaluation and Review Technique (PERT) was being independently developed in a military environment.

The US Navy, Lockheed Corporation, and management consultants Booz, Allen and Hamilton established the technique in only four months, in 1957. The main reason for developing the method was to speed up the Polaris project, which aimed to build the first nuclear armed ballistic missile (Morris 1997).

PERT and CPM are very similar techniques, and have the same advantages and disadvantages; therefore it is not a surprise that the methods soon merged and started to be called CPM/PERT. The only difference between the two techniques is that PERT evaluates the uncertainty, inherent in every project environment, by using three estimates for activity duration: pessimistic (p), most likely (m) and optimistic (o). The expected duration of an activity is then calculated as a weighted average by equation (2.1):

$$T = \frac{p+4m+o}{6} \qquad (2.1)$$

The expected duration of a project is the sum of the weighted activity durations on a critical path. In this way, the stochastic nature of a project is transformed into a deterministic one.

Although this technique might seem to be an effective way to deal with uncertainty, the evaluation of three estimates for every activity is difficult in practice (Cottrell 1999). The other aspects criticised by a number of researchers are the assumptions on which PERT is based. PERT assumes a skewed beta distribution, which is questionable (Garcia et al. 2010; Grubbs 1962). Cottrell (1999) describes one more problem with PERT; it does not address the merge-event bias problem. The merge-even bias problem means that attention is only paid to critical path activities, while the nearly critical paths are neglected. This results in delays caused by the interaction of merging paths.

2.2.3. Need for improvement

In addition to the previously defined shortcomings, traditional scheduling methods have been criticised for the fact that they neglect human behaviour (Stoop and Wiers 1996; MacCarthy et al. 2001; Jackson 2004; Son 2011). These researchers claim that neglected human factors are often one of the most significant causes of schedule overruns. Human issues and their management is becoming an increasingly popular area of research. However, the different aspects of human cognition are rarely emphasized in traditional scheduling (Stoop and Wiers 1996). MacCarthy et al. (2001) discovered that from 1970 to 1990 researchers did not publish any empirical studies on the human issues of planning and scheduling in the field of manufacturing. These two decades were during the age of belief in computers; software was the solution to all project management problems. More recent research focuses more on the human factor as an element of project success or failure (Cicmil et al. 2006; Schock et al. 2010). It has become widely accepted that humans make a project successful, not the methods or tools (Kenworthy et al. 1994; Winter et al. 2006).

Winter et al. (2006) provide an extensive literature review, criticising project management as being irrelevant to practice. Traditional deterministic project management tools are accused of being inappropriate in the dynamic environment of a project (MacCarthy et al. 2001), especially because they ignore human issues (Cicmil et al. 2006; Cicmil 2003), and hard and soft constraints (MacCarthy et al. 2001). Many mathematical solutions have been created but not used in practice (MacCarthy et al. 2001). Moreover, the results of the research (Jackson et al. 2004) showed that scheduling theory focuses on the sequencing of activities, allocation of resources, and optimisation solutions, while scheduling practices concern more social and organizational processes (Crawford et al. 2006). Deckers (2001 cited in Herroelen 2005), de Reyck and van de Velde (1999 cited in Herroelen 2005) performed research in the Netherlands and Belgium, which showed that even scheduling software was used more for communication and monitoring than for the optimization of schedules.

The discussed problems of CPM/PERT formed the grounds for the creation of Critical Chain Project Management (CCPM). CPM/PERT had to be improved to account for uncertainty, human factors, lack of procedures for multi project environment, problems related to frequently changing critical path, lost focus, and ineffective monitoring procedures.

2.3. Critical Chain Project Management (CCPM)

2.3.1. Terminology

CCPM is a controversial topic, and has both supporters and opponents. Disagreements among Critical Chain scientists start from the very beginning of the research - the terminology. A few authors use the term Critical Chain methodology

(Raz et al. 2003; Cohen et al. 2004; Schatteman et al. 2008), some call it a method (Winch and Kelsey 2005; Bevilacqua et al. 2009; Zhao 2010), others apply the more comprehensive definition - Critical Chain Scheduling and Buffer Management CCS/BM (Herroelen and Leus 2001; Herroelen et al. 2002; Hejducki and Rogalska 2005), while some even change the definition throughout their papers, for example from CCS/BM to methodology (Herroelen 2005; Herroelen and Leus 2005a). The term Critical Chain Project Management (CCPM) is used in this thesis due to the following reasons:

- CCPM is the most comprehensive term, which includes all of the above mentioned: methods, methodology, scheduling, and buffer management.
- CCPM is the term most frequently used in the scientific literature (Leach 1999;Long and Ohsato 2008; Yang et al. 2008; Stratton 2009; Tian, 2010).

2.3.2. Background

The discussion over terminology is also evident in the debate on the novelty of CCPM. Most scientists accept Goldratt as the developer of CCPM (Goldratt 1997). A few authors mention that the concept of CCPM was first introduced in 1990 at the International Jonah Conference (Bevilacqua et al. 2009; Watson et al. 2007). However, as the presentation did not lead to any scientific discussions, it is now generally accepted among researchers that the CCPM era started in 1997, when Goldratt published his scientific novel *Critical Chain.*

Supporters of CCPM claim that the best-seller book *Critical Chain* (Goldratt 1997) introduced a new breakthrough concept, the biggest sensation in project management since the development of Critical Path method in 1957 (Newbold 1998; Leach 2004). However, not all researchers agree. Some argue that Dr. E. Goldratt borrowed old ideas from the previous literature (Herroelen et al. 2002; Hejducki and Rogalska 2005; Trietsch 2005b). Trietsch (2005b) provides references to the primary sources of ideas:

- Critical sequence was mentioned for the first time by Wiest (1964 cited in Trietsch 2005b)
- Among other authors, the idea of inserting buffers was previously introduced by Trietsch himself (Ronen and Trietsch 1988 cited in Trietsch 2005b)
- The focus on the bottleneck idea was published by Perzovansky (1975 cited in Trietsch 2005b) and was well known in the USSR years ago.

However, despite attempts to evaluate the novelty of CCPM, even the severest critics agree on the successful contribution of Goldratt in integrating the well-known theories into one modern system. Moreover, the importance of CCPM lies not so much in its newness, but in the benefits it might bring to project management.

Disagreements among CCPM researchers on the issues of terminology and novelty are also noticeable in the debates around the advantages and disadvantages of CCPM. The supporters of CCPM, such as Robinson and Richards (2010), Newbold (1998) and Leach (2004), reject the critique and emphasize the successful implementation of CCPM in practice. The opponents, (Pinto 1999; Wilkens 2000; Raz et al. 2003; Trietsch 2005b) deny the advantages of CCPM due to the lack of scientific validation of the assumptions and methods proposed by Goldratt. According to Trietsch (2005b), the reason why CCPM researchers divide into those opposing groups is that Goldratt's "personality influences the academic debate". It is still necessary to objectively analyse all aspects of Critical Chain in detail, scientifically prove/disprove the underlying assumptions and methods of CCPM, consider its advantages, propose ways to improve it, and scientifically investigate both the successful and unsuccessful cases of implementation in practice.

2.3.3 Theory of constraints (TOC) and CCPM

The evolution of CCPM is based on the Theory of Constraints (TOC), which again was arguably created by Goldratt. Although Trietsch (2005b) claims that it is "not an actual theory" and proposes a new term "Management by Constraints", the terminology offered by Goldratt is widely accepted and used in the research literature. Goldratt introduced the TOC in his other bestselling novel *The Goal, 1989*. The theory was developed and applied to solving the problems in the manufacturing industry. Afterwards, the CCPM approach was developed by applying the principles of TOC in the field of project management.

The core of TOC is elevation of the constraint, which is the obstacle in the process of achieving the goal.

Although there are many ways to express the goal of a project, and a number of articles discuss how to measure whether a project is successful (Cao and Hoffman 2011), the principal goal of any project is to satisfy the need of all stakeholders, i.e. to deliver the full scope within the planned budget and time. In absolute-deadline projects (for example, the construction of an Olympic stadium or preparation of tender documents) the completion date is not changed, although the budget may be overrun and scope may be changed. In relative-deadline projects all of the three project output measurements may change.

The constraints in project management might be divided into several categories: physical, market, and policy (Watson et al. 2007). Physical constraints occur when there is insufficient equipment, an inadequate labour force, and a lack of materials, or when any other resources do not meet the project demand. Market constraint means that there is a lack of orders from the market, so even the most critical resources are forced to be idle, and the goal cannot be achieved because of insufficient demand from customers. The policy constraint occurs because of inadequate regulations, both formal and informal, that restrict goal achievement. Such regulations could include management policies, work procedures, communication, etc.

Having defined the goal and the constraints, TOC helps to achieve the goal by elevating the constraints in five focusing steps (Goldratt and Cox 1989):

1. “Identify the system’s constraint(s)
2. Decide how to exploit the system’s constraint(s)
3. Subordinate everything else to the above decision
4. Elevate the system’s constraint(s)
5. If, in previous steps, a constraint has been broken, go back to step 1, and do not allow inertia to cause a system’s constraint.”

2.3.3.1.CCPM steps

The five focusing steps of TOC applied to project management become the steps of CCPM. Researchers offer different sub-steps and their sequences (Newbold 1998; Cohen et al. 2004; Leach 2004; Lechler et al. 2005; Tukel et al. 2006; Chen and Peng 2009; Cui et al. 2010). The combined approach is presented in this work:

1. Identify the critical chain. The critical chain is the constraint of a project. It determines the overall project duration. In order to identify the critical chain the following sub-steps should be performed:

   1.1. Develop the primary baseline schedule. This step is exactly the same as for the process of Critical Path method (CPM).

      1.1.1. Determine the objectives of the project. Plan the budget and duration of the project, satisfying clients' needs (Newbold 1998).

      1.1.2. Identify the required activities. Work-Breakdown-Structure is useful in this stage.

      1.1.3. Define the precedence relationships of activities. The CCPM employs a finish-to-start relationship of activities in order to shorten the total project duration. Moreover, it applies an as-late-as-possible approach as this method improves the cash flow of the company, not requiring cash until it is absolutely needed. In addition, scheduling activities as late as possible saves the waste time, which might have occurred because of changes in a project's scope or specifications.

      1.1.4. Estimate durations, costs and resource requirements for activities.

1.2. Find the critical chain. Critical chain is the longest chain of activities that satisfies both the logical precedence relationships and the resource availability constraints. This is a new aspect of project scheduling compared to CPM, as it considers not only the precedence of tasks, but also pays attention to resource conflicts. Nevertheless, the problem of scheduling by CPM with consideration of resource constraints is well analysed in the literature under the name Resource Constrained Project Scheduling (RCPS). However, some researchers fail to distinguish the RCPS problem and the resource levelling. Usually they use these terms as synonyms (Raz et al. 2003). This should not be the case in scientific literature, as the terminology has different meaning. Resource levelling is defined as the "levelling resource use over the project horizon for a given project," while resource-constrained project scheduling means "minimizing the project duration subject to the precedence and resource constraints" (Herroelen and Leus 2005a). If the procedure of CCPM is stopped at this stage, it would be exactly the same as the RCPS problem.

2. Decide how to exploit the critical chain. There might be different solutions to the problem of how to exploit the critical chain. For example, it might be beneficial to review the schedule by looking for ways of shortening the duration by re-sequencing activities. There may be numerous ways to exploit the critical chain, and they depend on the particularities and the environment of the project itself. However, for all projects CCPM offers the following general sub-steps, which are discussed in more detail in separate sections of the thesis:

2.1. Reduce activity duration. Some authors (Cohen et al. 2004; Tukel et al. 2006) suggest performing this step prior to identification of critical chain. However, the sequencing of this step does not have any impact on the results, therefore both options are possible.

2.2. Insert the project buffer.

3. Subordinate the other tasks, paths and resources to the critical chain

   3.1. Insert the feeding buffers

   3.2. Reschedule after inserting feeding buffers

   3.3. Insert resource buffers

   Again, these specific CCPM sub-steps are discussed in separate sections.

4. Elevate the critical chain. The planned schedule should be evaluated against the objectives set in step 1.1.1. If the schedule is unsatisfactory, ways should be found to elevate the critical chain. The word 'elevate' is used by TOC professionals. It means that the solution might be to employ additional resources required to elevate the critical chain, to change the sequence of activities, to change the materials or equipment used, to re-assign resources from the non-critical activities to the activities on critical chain, to work overtime, etc. However, care should be taken when making decisions, as increasing project personnel beyond a certain level might increase congestion and project duration instead of decreasing it, resulting in lost productivity.
5. If in previous steps a constraint has been broken, go back to step 1.2.

Table 2.1 provides an easy way to compare the TOC and CCPM steps, including the main sub-steps of CCPM.

Steps 2.1 – 3.3 are explained in more detail in the following chapters.

	TOC	CCPM	
STEPS	1. Identify the system's constraint(s)	1. Identify critical chain	1.1. Develop the baseline schedule 1.2. Find the critical chain
	2. Decide how to exploit the system's constraint(s)	2. Decide how to exploit critical chain	2.1. Reduce activity duration 2.2. Insert project buffer
	3. Subordinate everything else to the above decision	3. Subordinate other tasks, paths and resources to the critical chain	3.1. Insert feeding buffer 3.2. Reschedule after inserting feeding buffers 3.3. Insert resource buffers
	4. Elevate the system's constraint(s)	4. Elevate the critical chain	4.1. Evaluate the schedule 4.2. Elevate the critical chain
	5. If, in previous steps, a constraint has been broken, go back to step 1, and do not allow inertia to cause a system's constraint.	5. If, in previous steps, a constraint has been broken, go back to step 1.2.	

Table 2.1. Comparison of TOC and CCPM steps

2.3.4. Activity durations

2.3.4.1. Human behaviour

All projects are performed in a dynamic environment. It is an inherent characteristic of project activity that its duration cannot be estimated exactly; one can only try to predict it. Among other factors, the precision of an estimate depends on the degree of uncertainty. There are many reasons for uncertainty; it may originate from the climate conditions, design changes, an inappropriate supply chain, etc.

The variation issues should be addressed since the beginning of schedule development. The safety time should be included in the project, and should protect the completion date of the project and ensure its robustness. However, the added time will increase the overall project duration, so the least possible amount of safety time should be added to the schedule.

However, contingencies in the project schedule can cause human behaviour problems. Due to human actions the safety time is usually wasted (Goldratt 1997; Leach 1999). In contrast to the Critical Path Method, which does not address any issues of human behaviour during scheduling and project execution, CCPM tries to solve several problems concerning the high impact of human actions in the project environment. These are Student’s Syndrome, Parkinson’s Law, multitasking, and overestimation of durations.

Student's Syndrome.

Referring to students, who usually perform the largest part of their assignments on the last night before deadline, Goldratt (1997) claims that human beings tend to delay their actions until they feel it becomes urgent. Being aware of the safety time in their task duration, they tend to work on other tasks which they believe have higher priority and are more urgent. In this way multitasking is related to student's syndrome.

The graphical presentation of Student's syndrome is presented in Fig. 2.1. It shows that a significantly small amount of work is performed in the first half of the activity duration (Leach 1999). The amount of effort needed to perform the task is inversely proportional to the remaining time of the task. This statement is valid for the whole duration of the activity, except the beginning of task, when a person puts a bit more effort into a new challenge.

Most of work is done during the last third of the activity duration. However, the shape of the curve in Figure 2.1 is not based on any research and there is no data to justify it. Moreover, the estimation of time is usually inaccurate. The pessimism of estimating durations, which prevails during the planning stage, is replaced by optimism during execution (Steyn 2001). However, not all aspects are taken into account, thus more time is usually needed than planned (Robinson and Richards 2010). Furthermore, when the person actually starts working on the task, uncertainty is revealed. Only at the last stage of work do these difficulties occur, and this leads to lack of time to complete the task.

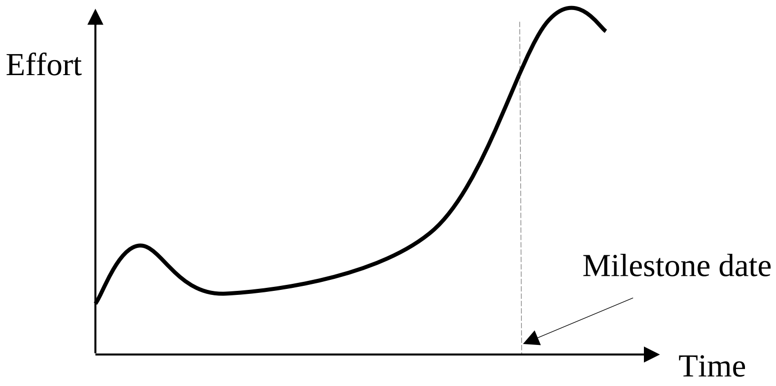

Fig. 2.1 Student's syndrome (Leach 1999)

Advocates of CCPM claim that removing the safety time from the activity duration eliminates Student's syndrome, as the person performing the task knows there is no time to waste; it should be performed as soon as possible.

Parkinson's Law

Another problem of negative human behaviour occurs because of Parkinson's Law. The law states that: "work expands so as to fill the time available for its completion" (Parkinson and Osborn 1957). There are many cases of empirical evidence for this law (Mannion and Ehrke n.d.-a) and attempts to solve the consequences of Parkinson's Law can be traced back to 1991 (Gutierrez and Kouvelis 1991).

The danger of Parkinson’s Law is that opportunities to shorten the duration of the project are not taken advantage of. People are reluctant to report early completion because of several reasons:

- Sandbagging. This is an American term for “requesting more time or budget than required” (Dilmaghani 2008; Robinson and Richards 2010,). Sandbagging is closely related to the fear of being asked to finish the task earlier in the future (Rand 2000). The performers tend to postpone the finish date in order not to be accused of previous sandbagging, and to protect the estimations of their future tasks with safety time.
- Previously negotiated extensions. The task performers do not intend to finish ahead of time if they had received an extension for their task before (Steyn 2001)
- Lack of incentives. There are no incentives to finish earlier. On the contrary, reporting the finish of work leads to the new task assigned.
- No basis for charging the projects. The companies, working on a contract basis, lose the grounding for charging the project in terms of salaries if the work is finished beforehand.

The above mentioned statements show that reporting work finished ahead of schedule seems to have more punishment aspects than incentives. Therefore people tend to use the following strategies to pretend working:

- Gold-plating or “polishing the apple” (Leach 1999; Dilmaghani 2008). Humans perform enhancements, which are not required for the project.
- 3 minute egg rule (Dilmaghani 2008). Referring to the duration of boiling an egg, the rule says that quality requires using all the time assigned. If a task is

finished earlier than planned, it is believed that quality is sacrificed. People pretend to be busy improving the quality and refuse to finish the task earlier than the set deadline.

- Assign a low priority to the almost completed task and postpone its finish.

Furthermore, projects consist of interdependent networks of activities. The extended duration of activities has an effect on the overall duration of the project, while the saved time is not taken into account to advance the project completion date. CCPM requires implementing the roadrunner behaviour, which implies that the activity has to be finished as early as possible (avoiding Student's syndrome) and has to reported as soon as it is completed (avoiding Parkinson's Law) to enable the start of proceeding activities.

Multitasking

In addition to promoting Student's syndrome, multitasking has further negative effects to the project performance. Multitasking is the frequent switching from one uncompleted task to another. It can take place in one project or between several projects. Multitasking differs from interruptions of work, which refers to a short discontinuation of work in order to complete another short task.

There might be different reasons why task performers multitask voluntarily. Some of them might agree to perform more than one task at a time because of a wish to impress their bosses; project superiors might ask for some progress on several projects at the same time in order to satisfy several clients.

The proponents of CCPM propose to avoid multitasking. They correctly state that multitasking extends the duration of a project, decreases quality, causes work stress for employees, and increases work in process (Mannion and Ehrke n.d.-b). The person, and the equipment, needs time to adjust when switched from one task to another. The required adjustment time depends on the task itself, as well as the person and their characteristics. Moreover, multitasking decreases productivity, and frequent disruptions might even lead to attention deficit disorder (Wallis et al. 2006). Multitasking leads to loss of learning curve efficiency, increased charges of hiring and firing, decreasing morale and loyalty of personnel (Hariga and El-Sayegh 2011). When multitasking is a usual practice in a company, there is less personal identification with project objectives (Reinertsen 2000). Finally, multitasking might bring significant harm when crucial information, feeding other activities, is received from performing one activity. In this case the activity should be performed and information gained as soon as possible.

Figures 2.2 and 2.3 illustrate how the eliminated multitasking can save time. Task A was performed in 4 days in an environment without multitasking, instead of 10 days when the multitasking took place. The duration of task B was also shortened by 3 days by avoiding multitasking. Only the last task, C, was performed on exactly the same day with or without multitasking. Although all three tasks were finished on the same day with or without multitasking, the duration of task A shortened by 6 days, and duration of task B shortened by 3 days. If any critical activity followed task A or task B, it could be started earlier in the case where multitasking was avoided, and therefore the project duration might be shortened.

In addition, Figures 2.2 and 2.3 illustrate a case where no adjustment time is needed. In practice, however, a person or a device would need time to adjust or be adjusted when moving from one task to another. Consequently, in the case of multitasking, task A would take longer to finish than10 days, task B would also take over 11 days to finish, and the same would apply to task C – it would take over 12 days to finish. Therefore the project duration would be extended, compared to the situation where multitasking was avoided. This illustrates an obvious improvement in task performance by eliminating multitasking.

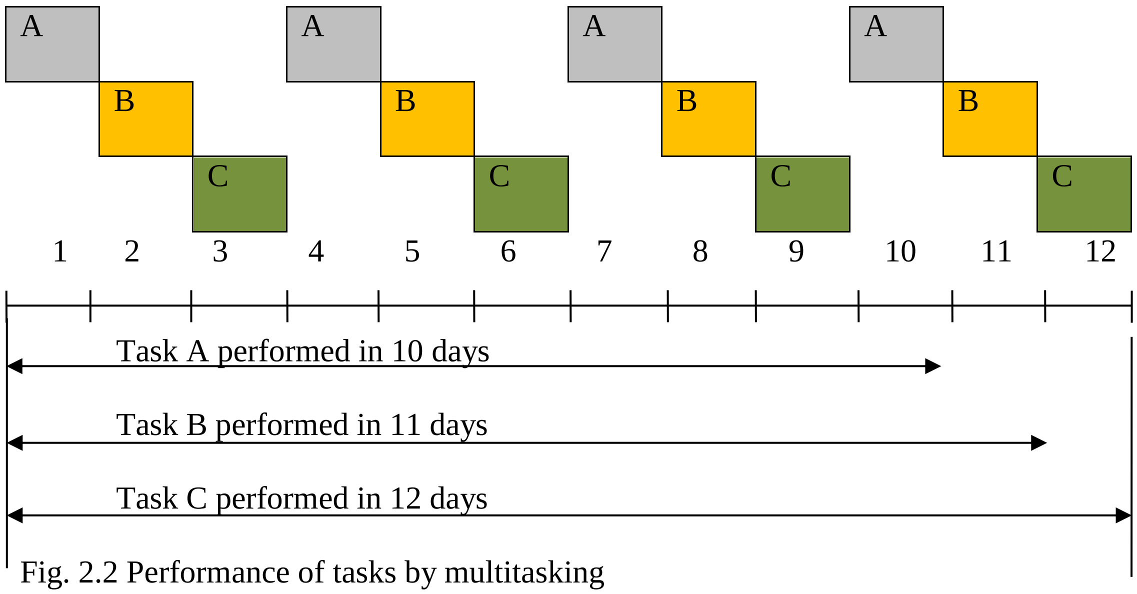

Fig. 2.2 Performance of tasks by multitasking

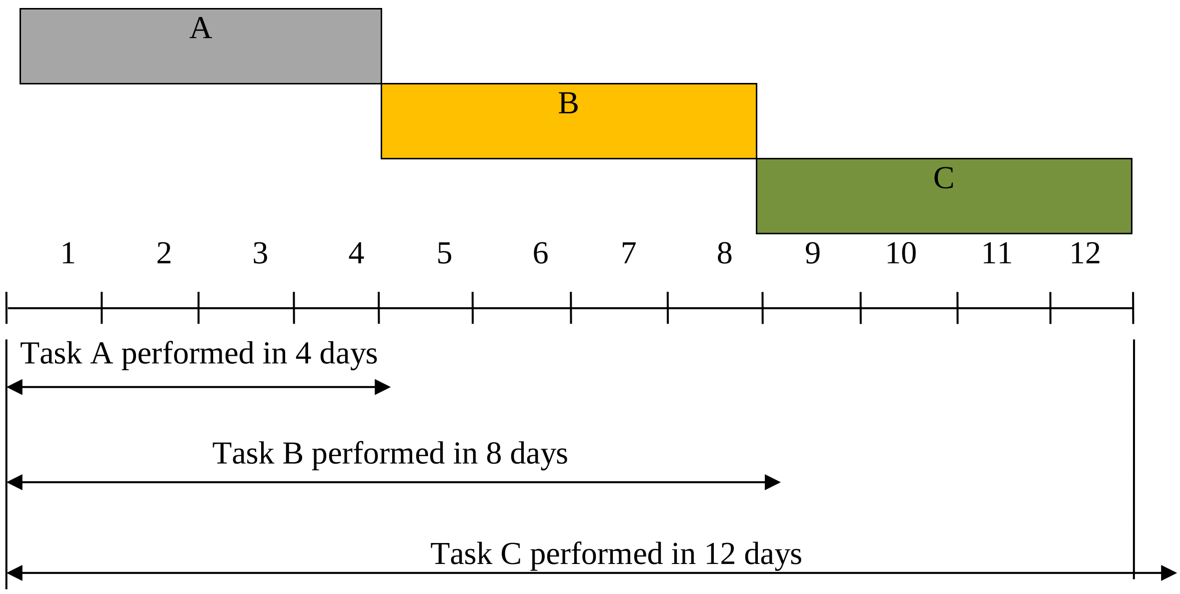

Fig. 2.3 Performance of tasks without multitasking

Overestimated activity durations

When estimating activity duration, project managers or estimators often ask task performers or task managers for their estimation. Baumeister et al. (2001) perform extensive review of other researchers' works, mostly based on observations, and reveal a general principle in human philosophy, that a bad factor has more impact than a good one. People acknowledge the negative effects of not meeting the deadline and therefore include safety time in their estimates. The same statement applies for task performers, task managers, project managers, programme managers and all the other positions within the organisational structure. When the activity duration is confirmed, it is inflated many more times than it should be. In addition, people inflate the planned durations due to the fear that their estimates will be cut before the initial baseline schedule is confirmed, for example, during the negotiation process with the customer. Referring to the padded historical data again leads to overestimated activity durations. Mohamed and Tucker (1996) provide an example from construction industry, where 25% time could be saved without additional investment in resources.

2.3.5. Reduced activity durations

CCPM manages variation by inserting buffers into the project schedule. Instead of dealing with the variation by adding the safety times into the estimates of separate activities, as in the traditional project management planning techniques, CCPM places the aggregated time at the end of the whole project. The principle of aggregation, borrowed from insurance sector (Kokoskie and Va 2001), allows the shortening of the whole project duration. Not only bad things will occur during the project; some activities will be delayed, while some of them will be finished earlier (assuming roadrunner behaviour takes place in the organisation). Therefore the aggregated safety at the end of the project should protect the project completion date with the same probability as in the case of safety times attached to separate activities.

The validity of the aggregation method is also proven by Central Limit Theorem, which states: “if independent probability distributions are to be summed, then the mean of the sum is the sum of the individual means, the variance of the sum is the sum of the individual variances, and the distribution of the sum tends to the shape of the normal curve regardless of the shape of the individual distributions”(Harris 1978). The more tasks are planned in a schedule, the more time could be saved applying the principle of aggregation (Geekie and Steyn 2008).

The original proposal by Goldratt (1997) to reduce activity durations was to use the median for activity duration. For the right skewed distribution this would mean 50% probability of finishing ahead of or meeting the deadline (Figure 2.4).

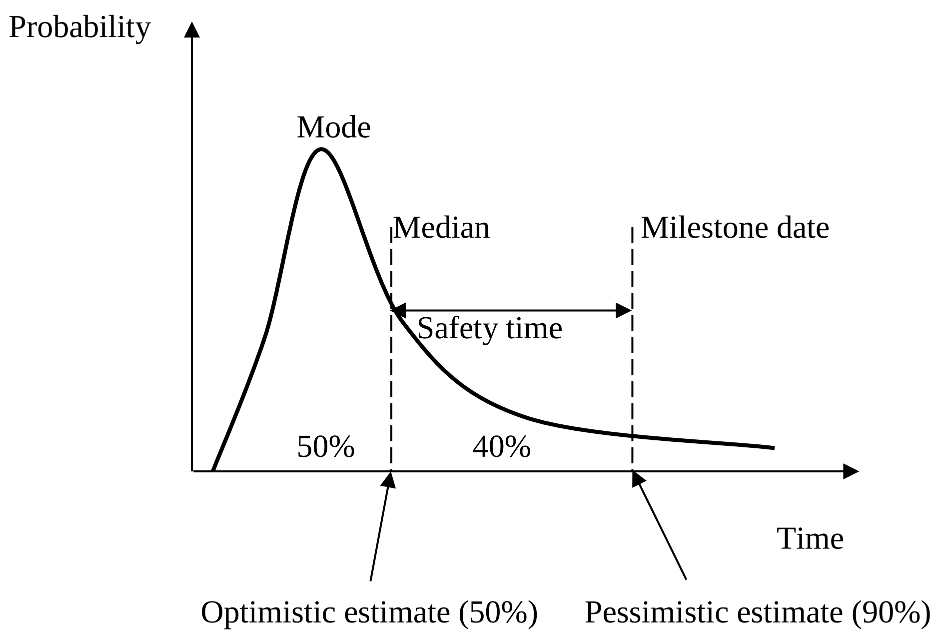

Fig. 2.4 Distribution of activity duration

2.3.6. Buffers

2.3.6.1 Types of buffers

The reduced activity durations decrease the robustness of a project and leave the due date unprotected. Therefore the buffers have to be applied. The buffers enable the shortening of project duration, help to generate robust schedules, and act as a management tool. Time buffers absorb the changes in actual activity durations during execution, thus protecting the baseline schedule from disruptions (Herroelen and Leus 2004; Lambrechts et al. 2008). In the single project environment, three kinds of buffers are used: project, feeding and resource buffers:

1. Project Buffer. As it has already been mentioned, in contrast to the traditional project scheduling where safety times are included in the durations of separate activities, CCPM consolidates safety times into the Project Buffer. This aggregated buffer is added to the end of the project to protect the completion date.
2. Feeding buffers are created to protect the critical chain from late finishes of the non-critical preceding activities. Feeding buffers are placed at the end of each non-critical path.
3. The resource buffer in the original CCPM methodology is the only non-time buffer. It is a virtual one as it does not have time, resources, or cost; therefore its name is a bit confusing. It is a different kind of buffer as it acts only as a signal, a warning mechanism for the resource to be prepared for work on the

critical chain activity when requested. The resource buffers are inserted when the activity on the critical chain is performed by a different resource.

Figure 2.5 demonstrates a simplified example of the inserted buffers in a CCPM schedule. The feeding buffer is placed at the point where non-critical chain (activities NC1 and NC2) joins the critical chain (activities C1, C2, C3, and C4). The resource buffer is placed before the activity C2, as it requires different resources from activity C1. The Project buffer is placed at the end of the project.

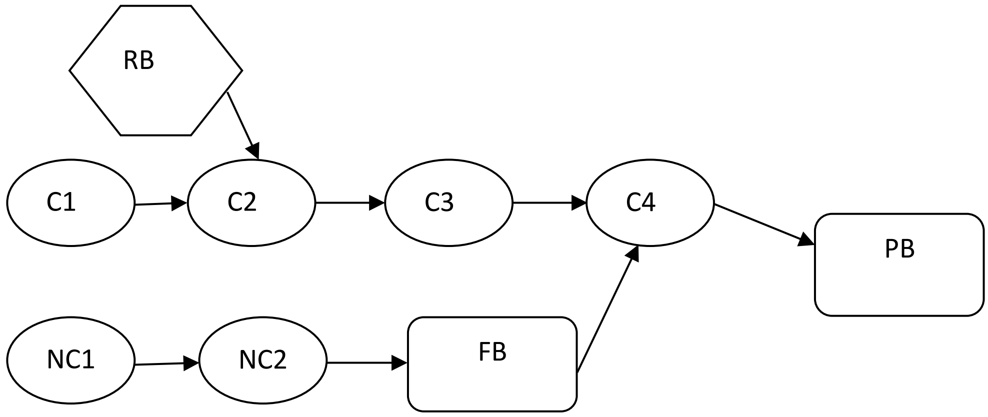

Fig. 2.5. Buffers in CCPM

Both resource and feeding buffers protect the critical chain from being delayed because of resource constraints and enable the performance by roadrunner behaviour, which enables early completion.

2.3.6.2 Sizing of buffers

Although there are no guidelines on how to determine the size of resource buffers, a significant amount of research has been done on sizing the project and feeding buffers. The size of buffer is a significant element in scheduling, as overestimated buffers lead to longer than necessary project duration, while insufficient buffers fail to protect the project from being overdue. There are mainly two methods for buffer sizing analysed in the literature: the cut and paste method (C&PM) and the root square error method (RSEM), sometimes called square root of the sum of the squares (SSQ).

The original rule proposed by Goldratt (1997) is to use 50% of the removed safety time for the project buffer, and 50% of removed safety time from the longest noncritical path leading to the critical chain for the feeding buffer. This proposal is called Cut and Paste Method (C&PM) in the scientific literature, and is demonstrated in Fig. 2.6.

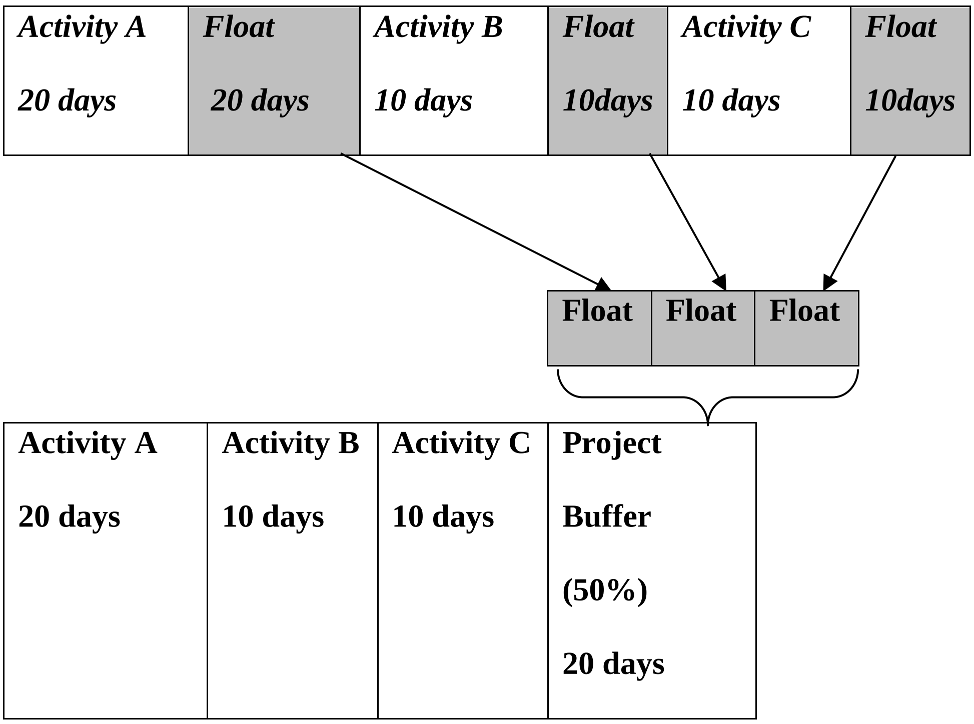

Fig. 2.6. Cut and Paste (C&PM) buffer sizing method

The C&PM is based on the statistical law which states that "standard deviation of the sum of a number of mutually independent random variables is less than the sum of the individual standard deviations" (Raz et al. 2003). In a beta distribution of activity durations the standard deviation is approximately 50% of the duration, which is the difference between the safe estimate of 90% probability and the shortened duration of 50% (Lechler et al. 2005). About one half of the activities in a project will finish on time or beforehand, while other half of the activities will not meet their deadline. Robinson and Richards (2010) provide a numerical example, demonstrating that application of 50% buffer sizing approach leads to approximately 25% shorter durations of projects compared to the resource levelled critical path schedules. However, without further research and data justification, these percentages cannot be generalised for other cases.

Another method demonstrated to perform better by Herroelen and Leus (2001) is the root square error method (RSEM). It does not create extreme cases – very large or very small buffers (Tukel et al. 2006). The RSEM applies two estimates for each task: the safe estimate of 90% probability S_i and the shortened estimation of 50% - A_i. The difference between these estimates is the activity duration safety. The size of buffer is then calculated as two standard deviations (Newbold 1998):

$$Buffer\ size = \sqrt{\left(\frac{S_1 - A_1}{2}\right)^2 + \left(\frac{S_2 - A_2}{2}\right)^2 + \cdots + \left(\frac{S_n - A_n}{2}\right)^2} \qquad (2.2)$$

The RSEM has received some critics. Herroelen and Leus (2001) argue that the formula is not valid for lognormal probability distribution. However, Ashtiani et al. (2008) claim that the 2SD approach does hold.

The more detailed example of CCPM network development is presented in Appendix D.

2.3.6.3. Buffer management

Buffer management simplifies the monitoring of a schedule during execution, as only 3 kinds of buffers need to be monitored in comparison to the hundreds of separate activities in CPM. Moreover, buffer management acts as a proactive tool for ensuring the robustness of the project schedule, as it does not allow the critical chain to change as often as it was in the case of critical path. It also focuses the attention of a manager on the most critical aspects, and provides a simple method for planning an action at the right time.

The recovery action planning involves division of a buffer into three equally sized areas, marked by different colours (Figure 2.7): green, yellow and red (Cerveny and Galup 2002). The risk of not completing a chain of activities is measured by the amount the buffers are consumed (Steyn 2001). Green colour marks the range of the buffer from its negative sign to one third of consumption. It indicates a safe zone, where no action is needed, showing that the project is going well. The penetration into the buffer only occurs because of the common variance in the duration. The yellow colour, which marks the range from 1/3 to 2/3 of the buffer consumption, indicates that preventive actions should be planned for the event if the buffer is consumed even more. The preventive actions include identification of the problem, developing the strategies to solve the problem, and the decision to monitor the progress of the chain more often or in more detail (Tian 2010). The red colour of buffer consumption shows the moment when the planned recovery action should be started.

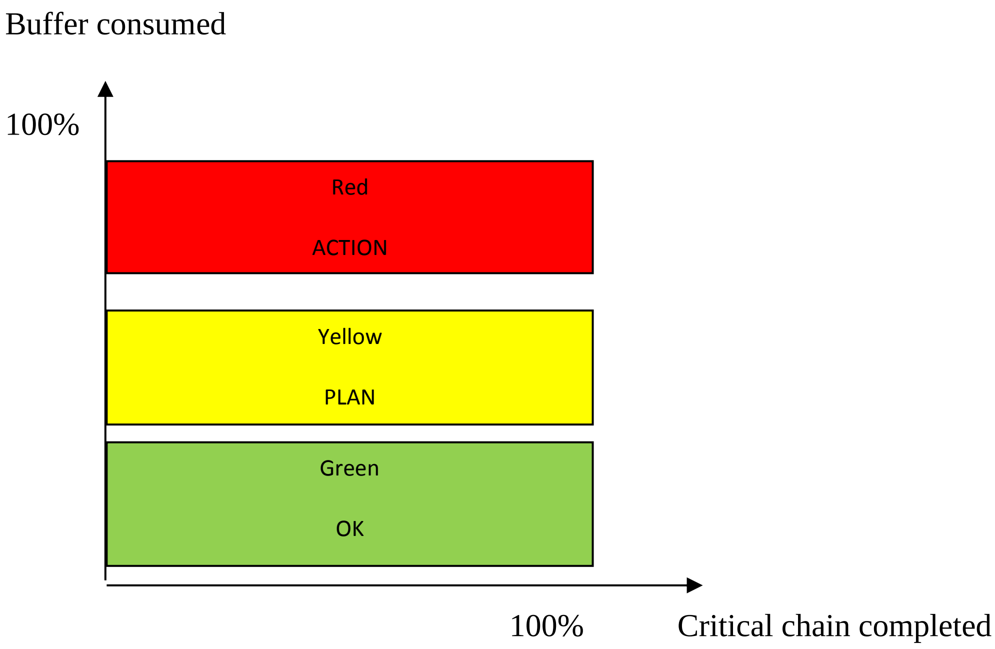

Fig. 2.7. Buffer monitoring in CCPM

The monitoring of buffers should be performed on the basis of the project specifics, and the management should decide on the frequency of buffer update. The tracking can be done every hour, daily, weekly or monthly. Leach (2004) indicates the frequency of no less than 1/3 of total buffer time. The update should be performed simply by requesting the information from the task performers about the remaining time to complete the activity.

2.3.7. Summary

Chapter 2.3 introduced the reader to the terminology and origin of CCPM. The literature review demonstrated the controversy of CCPM and revealed the significant advantages of CCPM over CPM/PERT. The CCPM:

- considers the availability of resources creating a schedule based on both activity precedence relationships and available resources;
- focuses on critical activities and resources;
- tries to overcome disadvantageous human behaviour: Student's syndrome, Parkinson's law, overestimation of activity durations and multitasking;
- applies roadrunner behaviour, which enables taking advantage of early finishes;
- shortens project duration and increases stability of a schedule;
- simplifies the monitoring of projects.

The shortened project duration, the increased stability of a schedule, the addressed human issues, and the implemented roadrunner behaviour are achieved with the help of the 3 types of buffers applied in CCPM: project, feeding and resource buffers. In CCPM the activity durations are reduced, and the aggregated time reductions are placed at the end of a project into a project buffer. Feeding buffers enable roadrunner behaviour by protecting the critical chain from delays in non-critical activities, while resource buffers protect the critical chain from the unavailability of necessary resources. The main methods for buffer sizing are the cut and paste method, and the root square error method.

2.4. Shortcomings and improvements of CCPM

2.4.1. Critical sequence

While CPM/PERT often deal with more than one critical path, CCPM has only one critical sequence – the critical chain. In cases where more than one critical chain exists, Goldratt's proposal is to choose any arbitrary chain (Goldratt 1997). This aspect has been criticised (Newbold 1998; Roel 2003; Leach 2004) with the argument that choosing the critical chain is an important decision, and should not be made on an arbitrary basis as it leads to different baseline schedules and consequently different durations for the whole project. Different suggestions have been made by researchers on how to select the most appropriate critical chain. Rabbani et al. (2007) propose to use domination rules for determination of critical chain. Robinson and Richards (2010) suggest applying the priority established for every task based on a relative current risk to the project.

2.4.2. Goal

The main objective of CCPM is shortening of the project duration, while the second objective is the minimization of work in progress (WIP) (Newbold 1998).

However, CCPM does not consider cost/profit-duration trade-offs, the time value of money, or opportunity costs. Additional objectives are neglected too; for instance minimisation of resource availability costs, maximisation of net present value, resource levelling, etc. (Roel 2003). The only research other than duration objective function in CCPM has been the analysis of the trade-off between stability and duration (Van de Vonder et al. 2005).

2.4.3. Task prioritisation

While CPM/PERT gives higher priority to tasks on a critical path, CCPM allocates higher priority to tasks on a critical chain, having the highest rate of buffer penetration ratio. However, the tasks of a strategically important project or the one associated with high penalties for delays might be more important than the buffer penetration ratio (Raz et al. 2003).

Suggestions made by researchers to date include prioritising activities by multiplying the average time, criticality index and cruciality index, to form an optimal subset of them (Rabbani et al. 2007). Another suggestion for determining the priority of tasks relates to the calculation of risk as a multiplication of probability and consequences (Bevilacqua et al. 2009).

2.4.4. Human behaviour

Parkinson's Law

Lecher et al (2005) argue that Parkinson's Law has not been proven to have significant influence on the duration of a project. Therefore its influence should be evaluated.

The problem remains of how to encourage people to report early finishes. Employees know that they will be reminded of a successful case and their duration estimate will be reduced next time. However, nobody can be sure that the risks avoided in the previous case will not occur the next time. Therefore employees are not motivated to report the early completion dates.

Multitasking

Some researchers disagree with the need to avoid multitasking. Reinertsen (2000) states, that multitasking creates necessary and beneficial conditions to link one project with another and share ideas between them. He claims that multitasking "reduces queuing problems and associate delays" because shared resources can be adjusted to resource demand, changing in time (Reinertsen 2000). In a dynamic environment, it would be difficult to implement a plan without multitasking when circumstances change. However, situations may arise where human resources cannot be shifted from one project to another, due to their unique expertise and specific knowledge. There might be cases where an activity cannot be split.

Moreover, critics emphasize that care should be taken when eliminating multitasking. Only “bad” multitasking should be avoided (Herroelen and Leus 2001; Trietsch 2005b). Trietsch (2005b) presents an example of “good” multitasking: three projects wait for an approval from the manager in order to proceed further on while manager is working on a large, time consuming activity. However, it is difficult to distinguish between “good” and “bad” multitasking in practice.

The general rule, combining the views of both the proponents and the opponents of CCPM should be: multitask with care.

Overestimation

CCPM is based on the assumption that people overestimate durations while planning (Goldratt 1997). Proponents of CCPM (for example Leach 2004 and Newbold 2014) do not question this assumption. They describe many reasons that individuals may inflate initial estimates of activity duration. These include accountability for your own estimate, and the later reduction of the estimate by other people due to different pressures. However, they neglect the fact that there are significant reasons for the underestimation of activity durations.

Flyvbjerg (2008) defines optimism bias as a “cognitive predisposition found with most people to judge future events in a more positive light than is warranted by actual experience”. Researchers note that not all people overestimate, and some might have optimistic evaluations leading to shorter than necessary durations. The proof of existing optimistic human behaviour has been discussed by researchers (Busby and Payne 1999; Russo and Schoemaker 1992; McCray et al. 2002; Kujawski et al. 2004; Son and Rojas 2011). Research on both the optimistic and pessimistic approach towards cost estimation is available (Britney 1976). However, the CCPM and its supporters (for example, Leach 2005) deny the existence of optimism bias in estimating activity durations. Others (Busby and Payne 1999; Raz et al. 2003) refer to the lack of empirical data to prove the validity of assumptions concerning overestimation.

Busby and Payne (1999) analysed the process of human judgement. They performed observations and conducted interviews with engineers. This revealed several reasons for underestimating the activity duration. One of them was the fear of job losses if the contract is not won. Another reason was pressure from other people to define a low estimate for the whole project in order to win the contract. Other factors that influenced overoptimistic estimations included the lack of estimating experience, and intensive competition. In addition, Busby and Payne (1999) point to the human tendency to be overconfident in our own abilities, and underestimate the time necessary to complete an activity ourselves, while the time necessary for others to complete a task is usually less underestimated.

Moreover, different people over or underestimate by different amounts. Given the same task, different people might give different durations. The amount of over- or underestimation depends on risk attitudes, which in turn are dependent on the knowledge and experience of the estimator, and the political and economic environment (Wang 2011). The estimation also depends on intrinsic motivation (enthusiasm to finish the task as early as possible) or extrinsic motivation (money or other kinds of reward, threat of punishment or other coercion) (Wang 2011). Optimism and pessimism are also related to the type and environment of a project (Kujawski et al. 2004). For example, in an environment where the late finish of an activity or project would be unacceptable, people tend to be pessimistic while estimating durations. However, personnel in higher positions know about pessimistic estimations in these environments, and usually cut the initial values of durations.

In addition to optimism and pessimism during estimation, there are the limitations of human judgement abilities. People usually "rely on heuristics or rules of thumb" (Tversky and Kahneman 1974). Winch and Kelsey (2005) interviewed planners from leading UK construction firms. The survey showed that most of the informants did not consider the project duration in a tender, but defined their own estimate for project duration. In most cases this estimate was longer than the one documented. They might rely on historical data or the knowledge of the estimators, but many of them were only confident in their own experience (Winch and Kelsey 2005). However, heuristics can lead to faults (McCray et al. 2002). Tversky and Kahneman (1974) describe availability and anchoring heuristics. The availability heuristic is associated with addressing information which just comes to mind, irrespective of the real frequency of its occurrence. People usually remember data which they are more familiar with, and consequently tend to over or underestimate risks and durations according to their previous experience. Anchoring heuristics show that people usually stay close to the initial estimate and do not sufficiently adjust historic or initial data. This also refers to the claim that "people tend to overestimate the probability of conjunctive events and to underestimate the probability of disjunctive events" (Tversky and Kahneman 1974). As a project is a series of conjunctive events, people tend to be optimistic about the probability of finishing on time. When evaluating risks (disjunctive events), they are more likely to be pessimistic. Confirmation bias (Wason 1960; Son and Rojas 2011) is associated with the human tendency to look for supporting data, but to ignore the conflicting information.

All of the described biases might lead to either loss making in business or lost business. When insufficient safety times are planned in project schedules, the business might make losses, and the projects might finish later than planned. When too large safety time is planned, opportunities to make business might be lost due to uncompetitive project durations, as they might not win the contracts. Unfortunately, research (Tversky and Kahneman 1974) has shown that human judgement cannot be controlled by motivating people to provide an estimate as accurate as possible with financial rewards or penalties. Son and Rojas (2011) claim that a collective mind (when a group of planners are working instead of separate individuals) could reduce optimism bias, but not completely. They state that even a group of people in a complex construction environment could be affected by optimism bias in the same way as individuals.

Nevertheless, the biases and human judgement heuristics must be considered while developing a baseline plan. CCPM might work well when durations are overestimated. However, it could be a complete catastrophe if the schedule was planned with an optimism bias and then CCPM was applied. When a schedule is compressed by 50%, the human resources are reduced by half and the budget is decreased. Therefore the reduction of activity duration cannot be done automatically, by just following the methodology and steps of CCPM.

2.4.5. Robustness

Robustness in CCPM relates to two issues: changes in schedule during the initial planning stage, and changes in schedule during project execution.

During the initial planning stage, the insertion of buffers might create difficulties. The inserted feeding buffers sometimes change the critical chain. The alternative path where a feeding buffer has been added might become longer than the critical chain itself, as shifting the activities of the noncritical chain backwards may create a situation where a noncritical chain has to be started before the planned beginning date of a project. Moreover, feeding buffers may create gaps in a schedule. Next, feeding buffers might sometimes fail to protect the critical chain when delays in non-critical activities occur. Finally, the insertion of both resource and feeding buffers can create resource conflicts. Solving the resource conflicts can become a total rescheduling problem.

Suggestions in recent literature aimed to overcome the pitfalls of buffer insertion include re-levelling after inserting buffers (Robinson and Richards 2010), not using the feeding buffers at all (Lechler et al. 2005; Long and Ohsato 2008; Peng and Huang 2013), and updating buffer sizes during execution (Herroelen et al. 2002). The latest proposal, however, may not always be beneficial as the robust schedule might bring more benefits than the shortened duration in certain cases (Roel 2003). Other authors propose local repair or global reschedule methods (Cui et al. 2010). Local repair involves the simple movement of the activities left (the ones which have resource or precedence conflict). Global reschedule means creating a completely new schedule, not considering the initially created one. The other proposal is to not assign the full resource capacity to activities in a schedule (Dilmaghani 2008), or to build an expert system, which would reset all the due dates (Blackstone et al. 2009). One more team of researchers propose to reschedule the project implicitly: to management judgement, min-slack or earliest due date to choose next activity; or explicitly: to compute optimal plan by forward pass (Lechler et al. 2005).

The second issue of robustness in CCPM schedules is related to the robustness during project execution. This means that the robustness of a schedule can only be evaluated in conjunction with the real life implementation. While the critical path is often changing during project execution, critical chain is said to be constant and rescheduling is not recommended, as buffers should protect from the changes in a schedule. However, the bottleneck resource is not stable (Raz et al. 2003; Stratton 2009). Equally, there might be cases where the shortening of the duration is more advantageous than the robustness of a schedule. Therefore rescheduling might be recommended when taking into account transaction costs (costs of communication, coordination and negotiation). The concentration on the stability of critical chain and avoidance of rescheduling might sometimes lead to the situation where the old critical chain is no longer the constraint of the project. Herroelen and Leus (2004) claim that "CCPM is not adapted for environments with very high uncertainty". Frequent rescheduling is required in high uncertainty projects as unforeseen new tasks are added.

2.4.6. Assumption of independent activities

Both CPM/PERT and CCPM assume that activities are independent. However, in real life the same factors might sometimes have an effect on different activities (for example, weather disruptions can influence several construction tasks at the same time). Therefore, the durations of activities will tend to change jointly, and the duration of the critical chain and project will be affected (Long and Ohsato 2008). Therefore the principle of aggregating safety times into PB and the central limit theorem might not be valid for CCPM, and the assumptions of statistical independence, on which both C&PM and RSEM buffer sizing methods are based, could be questioned (Raz et al. 2003).

2.4.7. Risk

A number of researchers have already tried to incorporate risk elements into buffer sizing methods. For example, Hong-Yi et al. (2014) introduced a risk transmission element into a schedule. New buffer sizing methods have been developed, which use three time estimates as in PERT (Jian-Bing et al. 2009; Li et al. 2010). Jian-Bing et al. (2009) offer to incorporate the effect of an activity position in a project: the further the activity is from the start of a project, the greater uncertainty it has. Li et al. (2010) suggest using the parameter of risk degree in the formula for calculating the project buffer size. However, there is no detailed explanation of how to quantitatively evaluate the degree of risk for this method.

The other researchers suggest buffer sizing in consideration to risk possibility and effect: bias Plus SSQ method (Leach 2004). Similarly, Liu and Kuo-Chuan (2009) state that a project buffer should include both the risk possibility and the effect of the duration extension. Bevilacqua et al. (2009) developed a method where the priority of activities is defined by a priority index, which is the multiplication of risk probability and consequences. Others agree that priority should be established for every task, and the buffer size determined on the basis of a relative current risk to the project (Fallah et al. 2010; Robinson and Richards 2010) or the safety time should be removed according to the measured uncertainty of each activity (Rezaie et al. 2009). One more research trend is to analyse the uncertainty and risk of separate activities and apply the scenario approach.

In addition to evaluating risk for each activity, the classification of activities into broader categories is suggested (Shou and Yao 2002). The authors develop a buffer sizing method, which classifies the activities into four categories, from low to high uncertainty. It enables the creation of different sized buffers for different safety levels, different activities and chains, as well as different types of projects. This is important as the C&PM and RSEM buffer sizing methods use linear procedure, which should especially be avoided in low risk environments as it leads to lost competition. On the other hand, in high risk environments the C&PM and RSEM might provide insufficient safety.

Additional research into combining CCPM with risk was performed by Schatteman et al. (2008). They propose to add elements of risk at the very beginning of scheduling to the activity durations. The researchers state that it is beneficial to use “the best case duration, not the mean or median, and to apply the simulated impact, depending on risk factors”. The risk quantification method, risk assessment and risk database, offered by Schatteman et al. (2008), all lead to defining an individual distribution for each activity's duration, in this way increasing stability.

Other ways to incorporate risk management into CCPM suggested by researchers include taking into account the risk preferences of various stakeholders (Jian-Bing et al. 2009), risk perception of scheduler (Zhang and Chen 2009), number of significant risks (Newbold 1998), and process risk (Hejducki and Rogalska 2005).

2.4.8. Activity duration

The cut of safety time from a separate activity is not an easy task. People overestimate (or underestimate) by different degrees. Raz et al. (2003) state that there are no proven methods or empirical evidence on the amount to be reduced.

CCPM proponents deny the importance of estimation accuracy. They believe that positive variation and negative variation equalize themselves. The supporters of CCPM argue that there can be no accurate data for the estimation of activity durations, as unquantifiable uncertainties will always exist, and therefore no perfect schedule can be created (Steyn 2002). Winch and Kelsey (2005) agree with Steyn stating that planning for longer than 3 months is futile, especially as the historical data may be not valid for the future, and the "stochastic modelling does not identify the cause of variation". Therefore CCPM proposes simply cutting 50% from the task duration, not going into detail about accuracy of the estimate.

However, the original proposal of CCPM to cut the activity duration time to 50% is often not the best solution. In fact, the percentage has no justification, and the decision is not always possible due to technological factors (for example, hardening of concrete). Indeed, there is no reason for cutting the estimations to 50% when the task is performed by mechanical apparatus (Rezaie et al. 2009). Moreover, it is not always possible to reduce duration to 50% because of "organisational, resource and financial dependencies" (Hejducki and Rogalska 2005).

Furthermore, researchers do not agree on the same type of activity duration distribution. The probability distribution of activity duration defines a chance for the particular activity duration. Although PERT uses skewed beta distribution, and the right skewed distribution is accepted in general for activity distribution function, some scientists advocate for gamma distribution (Winch and Kelsey 2005), some vote for beta distribution (Mannion and Ehrke n.d.-a), others apply the realistic lognormal or triangular (Kokoskie and Va 2001), while others suggest using exponential distribution (Blackstone et al. 2009; Cohen et al. 2004). Triangular distribution has the feature of being easy to calculate, while beta distribution is preferred because of the realistic shape and possibility to vary parameters to match the differently shaped estimates (Kokoskie and Va 2001). The approximation of beta distribution (normal distribution) is often applied due to its simplicity (Constructor n.d.). Moreover, the duration estimates of different activities follow different probabilistic distributions (Lechler et al. 2005).

Considering the loose ground on which the 50% suggestion is made, the researchers offer different solutions. One of the ways to overcome the shortcoming of CCPM is to apply Bayesian stochastic approximation (Cho 2009). Furthermore, in cases of low uncertainty, but possibly high human imprecision, fuzzy numbers can be used rather than the stochastic variables (Herroelen and Leus 2005b). Another suggestion is to use the direct fractile assessment method, which is said to be least biased and most reliable (Kujawski et al. 2004). Finally, researchers offer to borrow the contingency method from the finance sector and apply it to the graph schedules (Hejducki and Rogalska 2005).

Another method for making an estimate more accurate is the decomposition of the task into smaller elements. However, researchers agree that this is not an appropriate way of improving the reliability of an estimate (Busby and Payne 1999). Decomposition increases the possibilities of errors, creates too much work for analysis and a false sense of confidence (Kujawski et al. 2004).

The other proposals are related to the well-known traditional techniques. The estimating techniques for repetitive works should not be forgotten (Blackstone et al. 2009), the use of a learning curve or hierarchical estimation framework might be applied (Constructor n.d.), triangulation of methods used, or expert judgement and analogous estimating employed. The software for calculation of activity duration on the basis of data from the project database has already been created (Shou and Yao 2002).

Predictions could acquire a higher degree of precision by relating them to the past experience, interaction with the engineers and other project participants (Al Tabtabai et al. 1997). The information on activity durations is often available on databases from previous projects, and could be obtained by communicating with the participants of previous projects; although the latter source of information is not as reliable as written documentation. Very often, however, the appropriate historical data is unavailable (Bedford and Cooke 2001). Furthermore, even people who are familiar with activities can be very unsuccessful estimators (Tversky and Kahneman 1974). Additionally, the estimates from previous projects have to be based on the same conditions, the level and productivity of resources, and the same methods. This makes it very hard to apply historical data in practice. Estimators in the construction industry might use the data from The Building Cost Information Service price books, but according to Yang (2007), the possibility of determining the productivity of each working squad in the construction industry is very low. Furthermore, productivity rates have systematic and random influences. Although systematic influences could be considered, and the estimates corrected taking into account the benefits of the learning curve and average weather conditions, the random influences on productivity might be much more difficult to incorporate into an estimate. Finally, the estimate of duration is valid only if the same level of multitasking has been applied, which is very difficult to evaluate in practice.

The shortening of the duration should be made with care. Being aware of the reductions in task duration, people might simply double the duration of the estimate beforehand (Shou and Yao 2002; Raz et al. 2003). Estimations of durations are never perfect; therefore safety buffers should be added to protect the schedule and the due date. Unfortunately, although the shortening of durations must be related to the sizing of buffers (as the safety time from a separate activity is transmitted to the buffers), the recent literature focuses separately on either estimating the activity duration or optimising the buffer size (for example, (Rezaie et al. 2009). However, activity duration should be combined with buffer sizing. Kokoskie and Va (2001) agree with the noticed shortcoming of the previous research by stating that uncertainty in task estimates should be related to the buffer sizing method.

2.4.9. Project buffer

Early studies on the sizing of project buffers concentrated on comparisons of C&PM and RSEM. The advantage of the C&PM is said to be its simplicity and sufficiently large buffer. However, the 50% rule leads to excessive amounts of buffers needed (Herroelen et al. 2002; Lechler et al. 2005; Ashtiani et al. 2008; Schatteman et al. 2008). The reason is the linear procedure, which means that with the increasing length of critical chain, larger buffers are obtained. Although Goldratt (cited in Stratton 2009) argues that the rule is valid for any environment as the "buffer is a natural extension of the task time," the situation of linear increase does not always bring benefits as it creates larger than necessary project buffers, resulting in lost commercial opportunities. The C&PM might be more dangerous to apply in large projects. RSEM proved to perform better than C&PM (Kokoskie and Va 2001).

However, both methods have been criticised for being derived from pure mathematical procedures, and therefore being inconsistent with the nature of project management. In addition to the buffer sizing methods related to risk and described in Chapter 2.4.7, different proposals have been made to overcome the disadvantages of RSEM and C&PM. For example, Yang (2007) suggests calculating buffer sizes taking into account type of a project, Newbold (1998) proposes considering the confidence in resource availability, the number of tasks in a critical chain, and the importance of delivery time. Hejducki and Rogalska (2005) advice evaluating the influence of the technical and resource factors, randomness, and non-recurrence of a project.

There have been attempts to find the best method for buffer sizing based on the fuzzy set techniques instead of probabilistic ways to size the buffers (Tenera and Abreu 2008; Long and Ohsato 2008; Shi and Gong 2009). They claim that fuzzy techniques overcome the insufficiency in historical data. Zhang et al. (2014) suggest quantifying various uncertainties and computing their influences by the introduced fuzzy comprehensive evaluation method.

Other suggestions include the improved genetic algorithm offered for determining the size of buffer (Zhao 2010). Lambrechts et al. (2008) developed a time buffer allocation heuristic, which accounts for consequences of longer than expected activity durations caused by the resource breakdowns.

Recent studies into determining buffer size focus mostly on particular situations, scenarios, and schedule characteristics. Different factors are suggested for consideration. One of the methods proposed is determining the size of buffer in consideration of “the number of activities in chain, the uncertainty of activities duration and the flexibility of activities start time” (Yang et al. 2008). Other factors, taken into account during the development of the sizing model, are “the frequency of updates, task uncertainty and project service level” (Stratton 2009). One more improved method of buffer sizing was developed by Jian-Bing et al. (2009), which considers the flexibility and the position weight factors. Resource tightness and network complexity are also significant (Ma et al. 2014), and should not be neglected. Tukel et al. (2006) propose the adaptive method with parameters of resource tightness and density. Usually the network complexity indicates how dense the network is. Zhang et al. (2014) express the network complexity through the proportion of activity duration, flexibility of activity starting time and cost index; the resource constraints are expressed through resource efficiency and cost index.

Researchers also suggest applying Prospect Theory (Zhang and Chen 2009), or determining the size of buffer according to the average time and standard deviation of the most critical chain (Rabbani et al. 2007). Ma and Jiang suggest considering characteristics of the network structure (elastic coefficient and position weight). Buffer size should account for estimation errors or bias (Trietsch 2005a) and should be based on data from previous projects as well as the ratio between the cost of earliness and the cost of delay (Trietsch 2005b). Other researchers propose methods for buffer sizing which apply complexity coefficient, importance coefficient, risk degree, and adjustment coefficient of the manager's risk preferences (Zhang and Geng 2014). Shan et al. (2009) recommend sizing the buffer "based on the analysis of the risk event caused by accidental factors during project implementation". Yu et al. (2013) consider multi-resource constraints and resource utilization.

Current research goes even further, stating that buffer sizing should be dynamic, especially when new information is available, as constantly revised buffer sizes may point to new opportunities for shortening the project duration. Fallah et al. (2010) create an algorithm, which determines buffer size dynamically.

2.4.10. Feeding buffer

As already mentioned in Chapter 2.4.5. feeding buffers (FB), created to protect the critical chain against delays in feeding activities, create additional problems in CCPM. Firstly, feeding buffers might change the critical chain by shifting activities backward. In this case the feeding chain might start earlier than the critical chain. Secondly, feeding buffers might create gaps, which are then wasted due to Parkinson's Law and Student's syndrome. Next, feeding buffers might fail to protect when delays in non-critical activities appear. Finally, feeding buffers create resource conflicts.

A number of ways to improve the situation have been suggested. One of them is to re-level after inserting buffers (Robinson and Richards 2010), another is to remove part of the FB and add it to the PB (Yu et al. 2013), one more is to calculate feeding buffers first, followed by the calculation of a project buffer (Roel 2003). The suggestion for closing small gaps is to reduce the feeding buffer and to move the reduced amount to the project buffer (Leach 2003). Saihjpal and Singh (2014) analyse the insertion point of the feeding buffer when it creates a gap. The principle of the feeding buffer insertion point is created (Zhao 2010).

But the most cited way to overcome the problems created by feeding buffers is to eliminate feeding buffers from CCPM at all (Lechler et al. 2005; Long and Ohsato 2008). This approach is called a simplified CCPM (Roel 2003). However, proof is still needed that this suggestion is valid.

2.4.11. Implementation

Implementation of CCPM is related to high software and training costs. However, the commercial software is now available and the price of it is no longer an obstacle for implementation. The training costs are indeed high. They are associated with the need to change culture in a company, to change human behaviour, and even more importantly, to sustain the implemented changes. People have to adjust to a new system with no direct accountability, and different measurement attitude (no penalties, avoided attention to details). They must learn to avoid multitasking, and to report early finishes. All these learning processes require a significant amount of initial and continuous training, which leads to high costs for the company.

Raz et al. (2003) claim that successful cases of CCPM implementation have not yet been proven, as the successful companies did not have strong methodologies before implementing CCPM. In fact, there have been a number of failures to implement CCPM in practice (Lechler et al. 2005). Gupta (2005 cited in Dilmaghani 2008) gives numbers: only about one third of CCPM implementations from 150 attempts were successful. Furthermore, 15% of the successful implementations failed later on.

Two Master's thesis's have been written on the issues related to CCPM implementation. Repp (2012) investigated factors that influence CCPM success, while Verhoef (2013) analyses the reasons why people resist to work according to CCPM.

The analysis of an unsuccessful case could be useful to determine the reasons why some of the CCPM projects fail. The case and survey research of CCPM application are still very limited. There are some very brief video case studies, provided by CCPM software developer Realization Inc. However, it only provides an introduction to successful case studies, and thus concentrates more on selling their services than objective truth.

2.4.12. Subcontractors

CPM chooses subcontractors on the basis of the lowest cost, while CCPM looks into productivity and offers incentives for higher productivity. The basis for offering an incentive is that the cost of delay is higher than the cost of the financial incentive. The financial incentives also promote partnerships with contractors and increase business opportunities (Raz et al. 2003). Raz et al. (2003) note that the "incentive contracts and alliances have been considered a key of success recently". Together with incentives, penalties might be applied.

However, problems arise as not all projects have a right to offer incentives; for example government contracting (Geekie and Steyn, 2008). Moreover, there are ethical-cultural issues on prioritising projects on the basis of incentives, which are not discussed by CCPM researchers (Cook 1998 cited in Geekie 2008).

2.4.13. Software

General scheduling software has been analysed by researchers from several different points of view. Liberatore et al. (2001) reported an empirical study of the use of scheduling software in practice, Maroto and Tormos (1994) evaluated the quality of the software, Farid and Manoharan (1996) analysed different software packages from the resource levelling perspective, while Kolisch (1999) evaluated resource allocation possibilities. The studies resulted in proposals for software improvement, comparisons of better/worse performance of different software packages, and division of software into classes by how well the software allocates resources.

However, the CCPM software gets little attention by researchers. Therefore practitioners do not have any proven background to decide on the best choice of software. Researchers are not aware if any of the proposed improvements find their way in practical applications, additionally they are probably not familiar with improvements applied in practice, but not described in the research literature. To overcome this CCPM shortcoming, the author of the thesis has written an article analysing the implementation of the research proposals in the commercially available software (Appendix A).

In addition, Primavera is the most widely used software in construction industry (O'Brien and Plotnick 1999). However, there has been no software developed for Primavera, compatible with CCPM.

2.4.14. Monitoring

CPM/PERT might apply earned value analysis for monitoring the project, which is a difficult process in practice due to complicated collection of true and timely actual cost data. Instead of measuring project progress at the activity level, CCPM monitors at the project level by managing buffers. Managing buffers in a CCPM schedule means observation of buffer consumption, and the ratio of critical chain completion to buffer consumption. The ratio is also called performance or flow index:

$$Performance\ (flow)index = \frac{\text{CC complete (\%)}}{\text{PB consumed (\%)}} \qquad (2.3)$$

Although some authors indicate that “buffers add at least 10-15% to the number of items on the Gantt chart” (Raz et al. 2003), and create conditions for confusion among a variety of terms, tracking is time consuming (Lechler et al. 2005), the monitoring of three kinds of buffers is still simpler than hundreds of tasks. It has also been suggested that only the project buffer should be monitored, (Leach 2005), but this has not been proven yet by the scientific methods.

The initial suggestion to monitor buffers with just 3 zones (green, yellow, red) is now widely accepted to have been replaced by the more advanced Fever Chart (Dilmaghani 2008; Robinson and Richards 2010). It improves the early warning mechanism (Dilmaghani 2008). The Fever Chart employs the described monitoring of buffer consumption (green, yellow, red), and in addition provides the buffer penetration ratio. In this way preventive actions can be applied not only according to the size of buffer consumption, but also depending on the trend of consuming the buffer. For example, if several data points demonstrate that buffer consumption is constantly increasing; this also indicates that actions should be applied. The finish of a project in the green zone demonstrates that too much safety was built into the schedule. Fig. 2.8 illustrates an example of a Fever Chart.

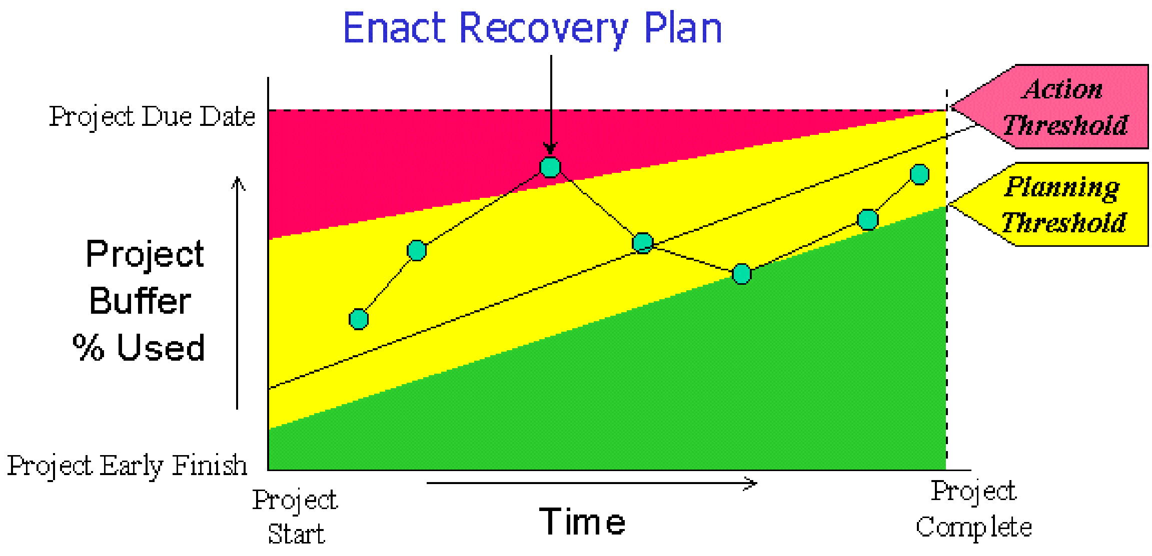

Fig. 2.8. Fever Chart (Roel 2003)

2.4.15. Recent research trends

Recently, more and more research has been done not about the optimisation of CCPM schedules or sizing of PB or FB, but on the issues related to the multi-project environment (Gupta 2003; Truc et al. 2012; Wang et al. 2014; Yang and Fu 2014; Zheng et al. 2014). This research, however, concentrates on the single project case.

2.4.16. Summary

The discussed literature review shows that despite the obvious benefits of CCPM over CPM/PERT, it still has significant drawbacks. There are numerous suggestions by researchers worldwide on how to improve CCPM. The most attention is paid to the sizing of project and feeding buffers, estimating activity duration, rescheduling, methods for determining the critical chain or defining priority for tasks, and integration of risk into CCPM. However, the suggestions still need to find their way in practice. The methods should be compared, and the most appropriate chosen.

The need for research on problems with human factors, guidelines for communication with external stakeholders, and motivation of subcontractors is identified during the literature review. Also, a case study of an unsuccessful implementation of CCPM would be useful for both researchers and practitioners.

2.5. Resource buffer

The analysis of the resource buffer is separated from the other improvements and shortcomings of CCPM, and is given in a separate Chapter as it is the most important section of the literature review in this thesis. The decision to investigate the question of resource buffers was made considering the availability of data, researchability, and timespan to perform the research. More importantly, the research on resource buffers in CCPM has so far received little attention by the academic community.

Resource buffers were introduced together with the methodology of CCPM in Goldratt's novel Critical Chain (Goldratt 1997). They were suggested in order to protect the critical chain from an unavailability of resources in the other chains.

The notice of an upcoming task might be a good alternative to the idle resource buffer when only human resources are working on a project. A human can be notified in advance, plan the time, and start working on a more important activity when required (if the unfinished task does not become critical because of the changed resource allocation). However, industries such as construction or production use not only labour, but also material, equipment and capital resources. For example, it takes much longer to receive capital equipment from international suppliers than domestic, which means higher uncertainty in the promised delivery date (Yeo and Ning 2002). There might be cases where notification to start work on an activity (for example, requiring expensive or rare equipment) will not be an adequate safety mean, as the resource might be being used for another uninterruptable activity, or might take long time to be ordered. Some resources have to go through the Engineer-Procure-Construct cycle before they become available for the project. The time buffer should protect the schedule from unavailability of equipment.

The problems in construction and similar industries involve not only unavailability of equipment, but also issues related to late or incorrect (incomplete or unsatisfactory quality) delivery. Early delivery might cause increased storage and inflation costs, or deterioration in material quality. However, the unprotected schedule might cause even higher financial losses due to the delayed finish of a project. Moreover, although CCPM offers significant advantages over CPM by arranging the activities by an as-late-as-possible approach (thus decreasing the waste time caused by changes in scope and specifications, and postponing the need for cash) the importance of resource buffers is even higher when activities are scheduled as-late-as-possible.

Most of the articles, analysing causes of project delay, particularly in construction projects, mention material or other resource related factors as having a significant influence on the project success. For example, in addition to other factors, inaccurate material estimating is identified as one of the main causes of cost overrun (Kaming et al. 1997). Odeh and Battaineh (2002) determined higher importance ranking for equipment and labour resources than material resources in the causes of construction project delay. Russell et al. (2013) provide a list of even 47 reasons why a time buffer is needed in construction tasks. Among other reasons for adding a time buffer, there were factors related to the labour force (reliability, availability efficiency, etc.), to equipment and tools (reliability, availability, productivity, time required to repair, time required to replace), and related to materials (incorrect quantity or quality, the wrong type of material or late delivery). Interestingly, the survey shows that causes of variation related to materials were among the top group causes for time buffers. However, foremen did not think of material related issues as one of the most important causes for buffering (Russell et al. 2013).

Resource buffers are analysed by a number of researchers, in disjunction from CCPM. Caron et al. (1998) create a stochastic model, incorporating safety stock and safety lead time for the materials in a construction site. Yeo and Ning (2006) claim that construction project managers usually apply resource time buffers between the promised delivery date and the required on site date, in order to protect the schedule from variation in promised delivery. They do not analyse the size of resource buffer, just state that it depends on the risk of particular equipment/materials, and the reliability of supplier. In fact, a survey shows that 87% of respondents in construction companies in Singapore add time buffer between the promised and the required date of major equipment to protect the schedule (Yeo

2004). The research in the last two publications (Yeo and Ning 2002; Yeo and Ning 2006) relates to CCPM. However, they do not analyse the size or allocation of resource buffer in CCPM, but apply the CCPM methodology to supply chain management.

Other researchers, again mainly in the construction industry, offer resource buffers not only as a time buffer, but as money, inventory or space (Russell et al. 2013). Others suggest using material and equipment buffers, or stage and activity buffers (Buchmann-Slorup 2014). Stage buffers are applied between the stages in projects in order to decrease the influence of unpredictable events, such as inclement weather. Activity buffers are applied for each activity in order to avoid fluctuations in productivity. However, activity buffers should be inserted only for the most sensitive activities. Again, these publications do not discuss the size of resource buffer. Kankainen and Seppanen (2003 cited in Buchmann-Slorup 2014) only explain that the size of resource buffer should depend on the "variability of a task's predecessors, the dependability of acquired subcontractors, and the total float of the task", and it should be "based on a balance between the desired duration of the project and the acceptable risk level".

To illustrate the need of resource buffer in CCPM the author has created a project example. Fig. 2.9 presents the network diagram of this illustrative example. It shows the critical tasks marked red and with a pattern in the box: Activity 1, Activity 3, Activity 7, and Activity 9. It also indicates the resources needed to perform these tasks. There are 5 types of resources in total: A, B, C, D, and E.

According CCPM, the necessary buffers are as follows:

- Feeding buffer between activity 5 and 7;

- Feeding buffer between activity 8 and 9;
- Project buffer after activity 9;
- Resource buffer before activity 7 for resources B and E.

Figure 2.10 shows the case when resource buffer is not inserted in a schedule. It can be seen that the critical chain is protected from delays in non-critical chains by using the feeding buffers. However, the critical chain is not protected from delays because of resource availability. The activity needs to have the necessary resources and finished predecessor activities to proceed. Although activities 2 and 6 are not directly linked by precedence relationships to activity 7, the delay of activity 2 or activity 6 would lead to the immediate delay of activity 7, which is one of the critical activities. It might also immediately consume a significant portion of the project buffer. This could be avoided if resource buffers were applied before activity 7 for both types of resources: resource B and resource E.

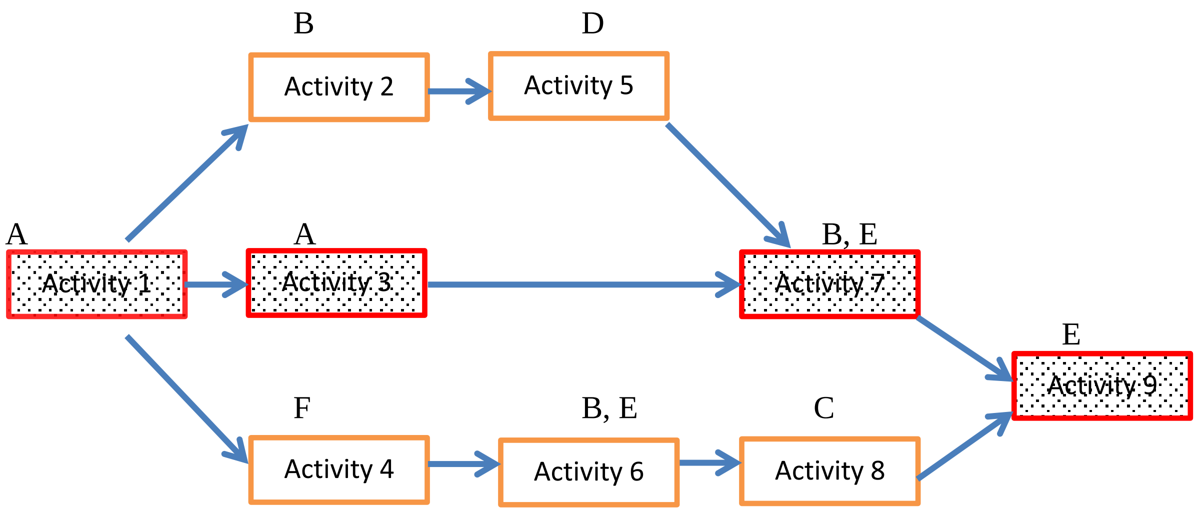

Fig. 2.9. Example of a project network

The Gantt chart of this network is presented in Fig. 2.10.

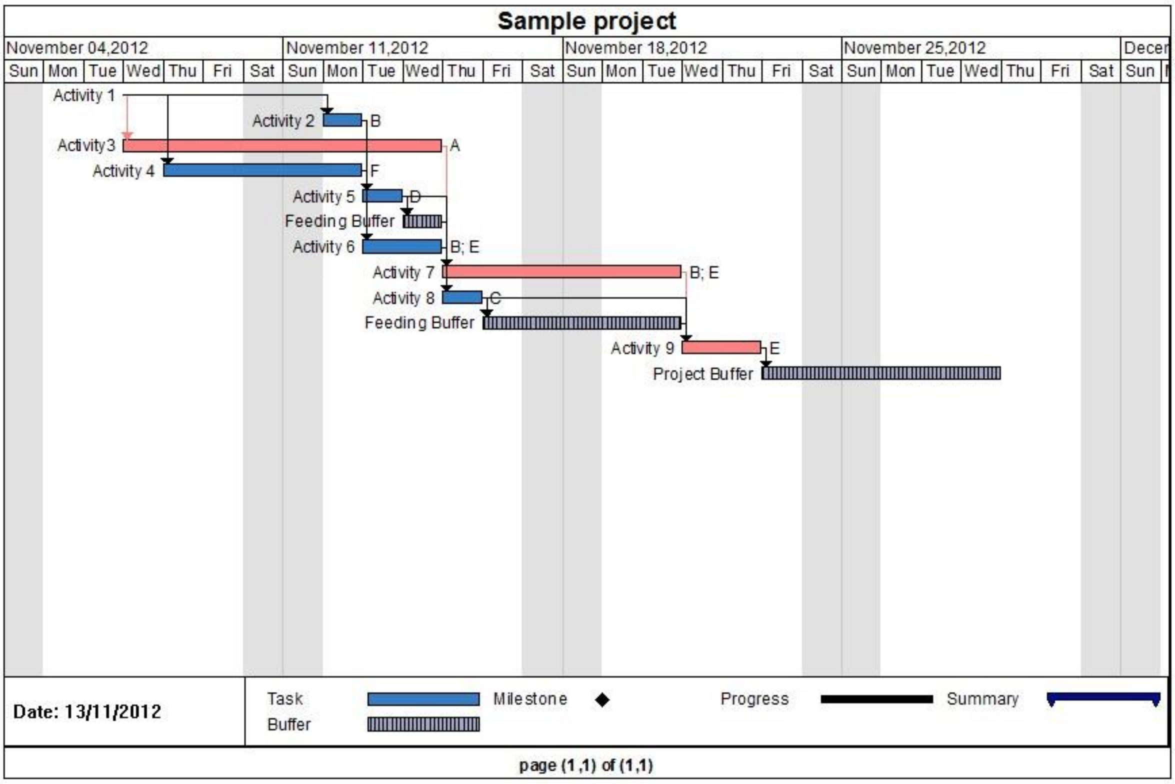

Fig. 2.10. Gantt chart of the illustrative example

In addition, CCPM suggests starting the activities on the critical chain as soon as possible. It states that some activities will be delayed and some will start earlier. Unfortunately, in case activity 3 finishes earlier, it would not be possible to start the next critical activity 7 sooner than planned as resources B and E would still work on activity 6. Applying resource buffers could create the necessary conditions for starting work earlier than planned and taking advantage of early finishes.

Surprisingly, little attention is paid to the issue of resource buffers by researchers. Although most of the articles still describe resource buffers alongside project and feeding buffers (Bevilacqua 2008; Zhao 2010), some of the articles on CCPM do not mention the resource buffer at all (for example, Peng and Huang 2013). To the best of author's knowledge, only a few articles have been published in the field related to CCPM resource buffers. One of them uses simulation to demonstrate that planning of idle resources might bring benefits in a multi-project environment (Ben-Zvi and Lechler 2011). Lambrechts et al. (2008) demonstrate that resource buffered schedules are advantageous in terms of a minimized schedule instability cost when resource availability is uncertain (subject to resource breakdowns). The size of resource buffer in the production environment is analysed by Radovilsky (1998). However, the sizing and allocation of resource buffer, which would be applied in the single project environment and would be related to CCPM, still lacks attention.

Research on CCPM software reveals a similar situation. The only software which claims to use resource buffers, is Agile CC. However, Agile CC applies it only in a multi-project environment, where it should be called a capacity constraint buffer, rather than a resource buffer. All other software developers have decided to eliminate resource buffers from the newest versions of their products, one of them stating: "We have found schedule update meetings are a better way of communicating the same kind of wake-up call" (ProChain User's Guide 2011, p. 144).

However, resources do not just have potential to become bottlenecks in a multi-project environment, where a capacity constraint buffer is used according to CCPM methodology. The resources might also be linked to each other in single projects, and resource bottleneck might exist. The tasks on the critical and other chains need to satisfy both the precedence relationships and resource availability constraints in order to proceed. It is surprising that the capacity constraint buffer is acknowledged and widely used to protect the schedules from resource unavailability among multi projects, while the single project is viewed as bottleneck free, or at least the importance of bottleneck protection is not considered. On the other hand, research on the capacity constraint buffer in the field of project management is also very scarce, and the percentage for the capacity constraint buffer is used for defining its size. Unfortunately, this percentage is not justified in any research.

The size of resource buffer is a significant question, as too small a resource buffer will not protect the schedules from delays, while a resource buffer that is too large may unnecessarily increase the cost of a project.

The review given in this Chapter shows that the research questions raised in this report are worth exploring, and will provide a significant contribution to the body of knowledge in the field.

2.6. Conclusions

The literature review on traditional project scheduling methods and CCPM demonstrates that CCPM addresses the human issues neglected by CPM/PERT, promises shorter delivery times, a more robust schedule, and simplifies the project monitoring. Having a number of important advantages, it still requires more research on issues related to human factors, stakeholders and success factors. Most of the research so far has been done on the issues of activity duration, risk integration, and the sizing of project and feeding buffers. However, the equally important topic of resource buffers has been completely neglected by CCPM researchers.

Resource buffers are beneficial in the fields of research other than CCPM. However, in CCPM, where non-critical activities are scheduled as-late-as-possible, resource buffers would be even more useful. They would also help to ensure the earlier than planned start of critical activities is possible.

The question of the needed resource buffer size is under-researched. It is important to determine the size of resource buffer large enough to protect the schedule and take advantage of early finishes, but small enough to make more money from the project.

3. RESEARCH METHODOLOGY

3.1. Introduction

The research methodology chapter starts with the research design: the philosophical assumptions and research strategy applied for the research. This is followed by a description of the procedures and tools used in this research: the creation of a simulation model for the purpose of this research and the development of a generalised simulation algorithm for use by other researchers/practitioners. Software applied in this research is discussed. The outline of Chapter 3 is provided in Figure 3.1.

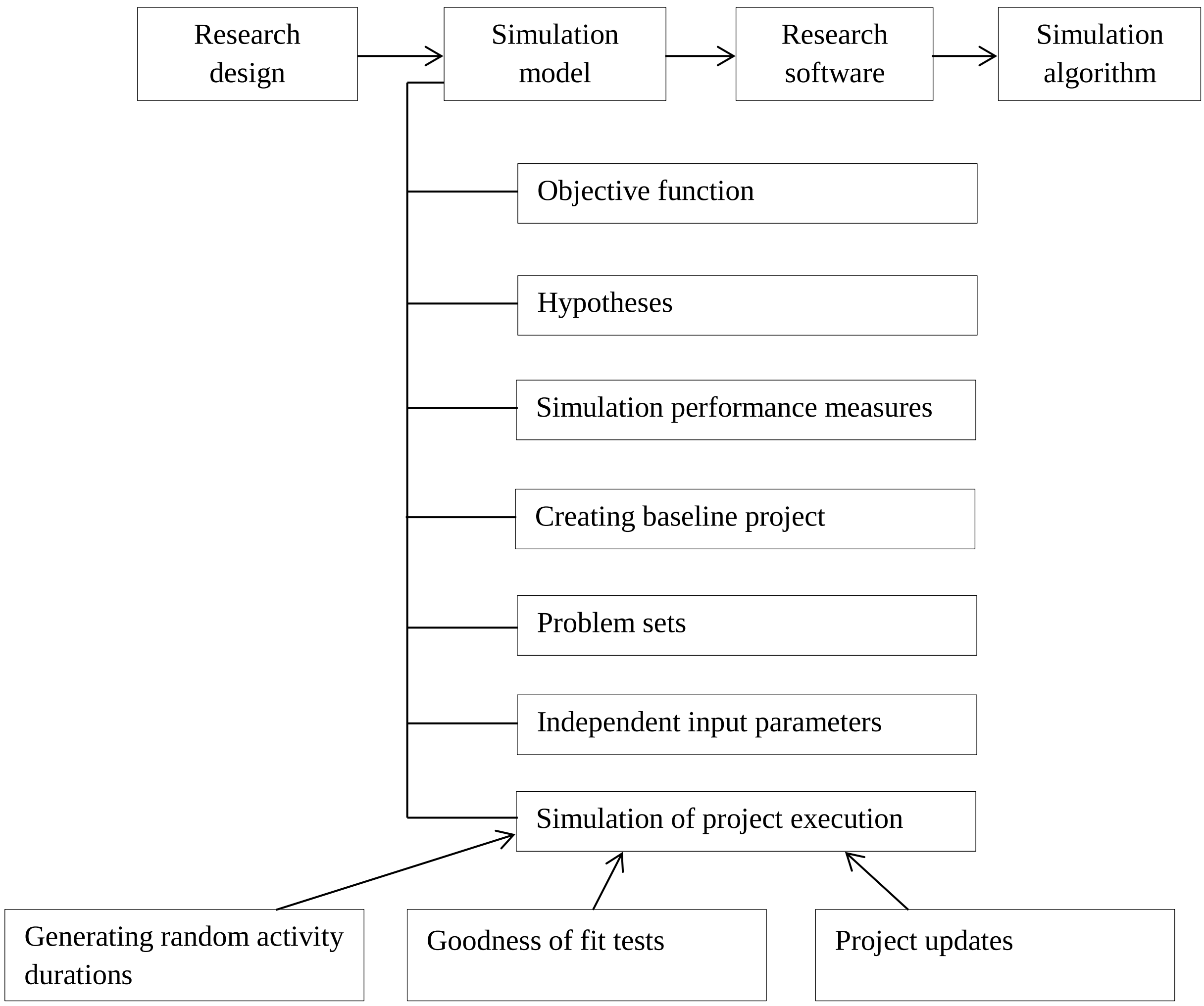

Fig. 3.1. Outline of Chapter 3

3.2. <u>Research design</u>

At the start of the research design, philosophical assumptions had to be made. Saunders et al. (2012) provide a very useful table, summarizing research philosophies (Table 3.1). This table explains concisely but clearly the terminology of ontology, epistemology and axiology. It also compares four main philosophies in management research.

The research for this thesis reflects positivism philosophy. The creation of rules for buffer sizing and allocation is seen as the creation of knowledge, which is objective and not aimed at subjective understanding and interpretation from different points of view by human minds. Therefore, positivism is more appropriate then interpretivism for this research. Moreover, Saunders et al. (2012) claim that the positivistic research deals with observable data. It often uses hypotheses development and then analyses them to confirm/reject. It deals with the facts rather than impressions. Therefore the researcher is separated from the data and remains objective throughout the research. The researcher also remains unbiased. The researcher's upbringing, cultural experiences and world views do not influence the research. Because of these reasons, the positivistic approach suits this research more than the realism philosophy.

	Positivism	Realism	Interpretivism	Pragmatism
Ontology: *the researcher's view of the nature of reality or being*	External, objective and independent of social actors	Is objective. Exists independently of human thoughts and beliefs or knowledge of the existence (realist), but is interpreted through social conditioning (critical realist)	Socially constructed, subjective, may change, multiple	External, multiple, view chosen to best enable answering of research question
Epistemology: *the researcher's view regarding what constitutes acceptable knowledge*	Only observable phenomena can provide credible data, facts. Focus on causality and law like generalisations, reducing phenomena to simplest elements	Observable phenomena provide credible data, facts. Insufficient data means inaccuracies in sensations (direct realism). Alternatively, phenomena create sensations which are open to misinterpretation (critical realism). Focus in explaining within a context or contexts	Subjective meanings and social phenomena. Focus upon the details of situation, a reality behind these details, subjective meanings motivating actions	Either or both observable phenomena and subjective meanings can provide acceptable knowledge dependent upon the research question. Focus on practical applied research, integrating different perspectives to help interpret the data
Axiology: *the researcher's view of the role of values in research*	Research is undertaken in a value-free way, the researcher is independent of the data and maintains an objective stance	Research is value laden; the researcher is biased by world views, cultural experiences and upbringing. These will impact on the research	Research is value bound, the researcher is part of what is being researched, cannot be separated and so will be subjective	Values play a large role in interpreting results, the researcher adopting both objective and subjective points of view
Data collection techniques most often used	Highly structure, large samples, measurement, quantitative, but can use qualitative	Methods chosen must fit the subject matter, quantitative or qualitative	Small samples, in-depth investigations, qualitative	Mixed or multiple method designs, quantitative and qualitative

Table 3.1. Comparison of research philosophies (Saunders 2012, p.119)

Once the research philosophy was defined, the research strategy was selected. Saunders et al. (2012) discuss the main research strategies: experiment, survey, case study, action research, archival research, grounded theory, archival research and ethnography.

Here the main points of different research strategies are described, which served as the basis for not selecting them for this research. The statements are based on the literature from Saunders et al. (2012). Applying ethnography research strategy, "the researcher needs to immerse herself or himself in the social world being researched as completely as possible". The archival research requires documents and records as a source of data. Action research focuses on change and action. Survey and case studies require empirical investigations and data. The empirical data, as well as the archival data was not available for the purpose of research on resource buffers.

To answer the research questions set in Chapter 1.2, an experiment was chosen as the most appropriate research strategy. The purpose of an experiment is to study the causal links (Saunders et al., 2012). This research tries to analyse the link between the size of resource buffer and the total project duration. Saunders et al. (2012) claim that an experiment typically involve:

- Definition of a theoretical hypothesis. In this research hypotheses are defined in Chapter 3.3.2.
- Selection of samples of individuals from known populations. In this research projects are chosen with the known network characteristics (Chapter 3.3.5).
- Random allocation of samples to different experimental conditions. In this research the experimental conditions were changed for all samples (projects).

- Introduction of planned intervention or manipulation to one or more of the variables. In this research the sizes of resource buffers and uncertainty levels were manipulated.
- Measurement on a small number of dependent variables. In this research the changing duration of analysed projects is recorded.
- Control of all other variables. In this research all other variables are kept constant.

Once the experiment was chosen as a research strategy, the next step was to determine the data collection and analysis technique. There are two main options: quantitative or qualitative. A mixed approach is also possible. Quantitative data collection and analysis technique generates or uses numerical data, while qualitative technique generates or uses non-numerical data.

As positivistic research philosophy relates more to a quantitative approach (Cavaye 1996), the quantitative methods were considered to be the most appropriate for this research. Applying the positivistic approach, the observations are usually quantifiable and statistical analysis of results is possible (Saunders et al. 2012).

As already mentioned, in order to perform an experiment the input of data is necessary, together with one or more parameters that are manipulated, and other parameters that can be controlled. Unfortunately, achieving these requirements for an experiment in a real life project was impossible. Therefore 'laboratory' conditions had to be created, and a computer experiment had to be performed. To perform this artificial experiment, the simulation method was chosen. Banks et al. (2001) define simulation as "the imitation of the operation of a real-world process or system over time”. Simulations are often applied when real life experiments are inappropriate because they are unacceptable, dangerous or impossible to perform (Sokolowski and Banks 2009). In addition, the cost and the time of a simulation is significantly lower when compared to an experiment in a real life environment. Furthermore, a simulation can be applied to the same project many times, whereas in the real world it is unlikely that the same experiment could be repeated many times, whilst still keeping complete control over constant parameters.

In fact, most of the publications on CCPM research are based on quantitative methods of research. The most popular method applied by scientists searching for the ways to improve CCPM is also the simulation of projects: for example, Kokoskie and Va (2001), Cohen et al. (2004), Rezaie et al. (2009), Tukel et al. (2006), Asthiani et al. (2008), Yang et al. (2008), Cui et al. (2010), Lambrechts et al. (2010), Wu et al. (2010).

3.3. <u>Simulation model</u>

3.3.1. Objective function

Critical Chain Project Management deals with the minimization of project duration as the most important objective. However, without protecting the critical chain from lack of resources, the planned minimum project duration might extend during project implementation. Applying resource buffers should protect the minimum duration required to finish the project. However, resource buffers will increase the inventory costs and other associated operating expenses. Analysis of resource buffers cannot be related to duration only. It also has to include financial parameters: the cost of the resource buffer use and the financial benefits of early project delivery.

The minimum project duration was still chosen as the primary objective function for this research. Having said that, financial issues are also explored and discussed in Chapter 5.3-5.4.

3.3.2. Hypotheses

The following hypotheses were created:

Hypothesis 1. *Application of resource buffers on average shorten project duration.*

Hypothesis 2. *The higher the uncertainty of the project environment, the larger the resource buffer should be.*

Hypothesis 3. *There is an optimum size of resource buffer, expressed in the percentage of the time resource is planned to work without interruptions before starting the work on a critical chain, common across all projects.*

3.3.3. Simulation performance measures

The most significant measure of simulation was the project duration. Information regarding whether the project was late or finished on time was also recorded. The average as well as the minimum and maximum values of project duration during simulation were noted. It was observed if the inserted resource buffers caused resource conflicts in schedules.

3.3.4. Creating a baseline project

The project baseline schedule was created according to CCPM methodology. The feeding buffers (FB) were applied, as well as a project buffer (PB). Obviously, the 50% rule is not the most beneficial, and a number of more advanced and justified methods have been suggested by researchers (see Chapter 2.3.6.2 and chapter 2.4.10). The 50% rule for FB and PB sizing has been shown to provide larger than needed safety times (Herroelen et al. 2002; Lechler et al. 2005; Asthiani et al. 2008; Schatteman et al. 2008). Excessive protection might not use the benefits of resource buffers, as FB and PB might be enough to protect the schedule. Decreasing the size of safety time provided by FB and PB makes the resource buffer even more significant. Therefore, if the developed hypotheses are valid when excessive protection is used; they will be valid applying more advanced FB and PB sizing methods, which generate smaller buffers. This justifies the selection of the 50% PB and FB sizing rule for hypotheses testing.

If the inserted FB changes critical chain and prolongs project duration, the FB was split and part of it was added to the PB to keep the start day of the project and the critical chain the same.

The resource constrained project problem was solved by the Agile CC software. The explanation why this software was selected for the research is given in Chapter 3.4. The algorithm applied in this software is proprietary. Therefore, it is not known how the scheduling problem can be solved. The option could be to solve the problem by the branch and bound algorithm, cited as the most effective (Demeulemeester and Herroelen 2002). However, this again would unnecessarily complicate the simulation process. As the same software is applied for the simulation of all projects, it is possible to analyse the influence of resource buffers irrespective of the method chosen to solve the resource constrained project problem. Therefore, the algorithm encoded in Agile CC was used for this research.

CCPM uses the term resource buffer, but does not assign any cost or resources to it. This research applies resource time buffers the same way as feeding and project buffers. The resource buffer has allocated resources.

3.3.5. Problem sets

Some researchers use an example of a real project network (Bevilacqua et al. 2009) or artificial project networks (Sun and Xue 2001) to analyse the problem and perform analysis. However, increasing the number of project schedules helps to address the validation of simulation results. Moreover, the randomness of generated project networks further increases the validity of the results. Herroelen (2005) states that the combination of analysed projects should reflect the complete range of problem complexity and unique characteristics to represent the real life project scheduling problems. Therefore, the selection of the set of project instances is a crucial step in simulation design.

In the articles related to CCPM or project scheduling in general, it is widely accepted to use the data set of 110 Patterson problems (Tukel et al. 2006; Cui et al., 2010). Patterson problems include a set of 110 schedules with different numbers of activities (Patterson 1984). However, these 110 schedules have not only different numbers of activities, but also different network and resource availability characteristics. It becomes hard to select a few projects with the similar characteristics for comparison. Another frequently used database of project networks was developed by Kolisch and Sprecher (1997), and is called The Project Scheduling Problem Library (PSPLIB). PSPLIB schedules are used "as an almost standard test set for resource constrained project scheduling problem" (Herroelen 2005, p. 422). The PSPLIB data set and 110 Patterson problems have an advantage as they provide opportunity to compare the research results with the given benchmark results. However, these benchmark cases have been found for critical path method, not the critical chain. Therefore, the advantage of being able to compare the results with the benchmark is not applicable to this research. On the other hand, the benchmark results for critical chain project management (CCPM) do not exist in any of the project schedule generators. Furthermore, the above mentioned Patterson and PSPLIB project schedule sets have acquired criticism from researchers (Demeulemeester et al. 2003; Herroelen 2005). Demeulemeester et al. (2003) demonstrate that networks in PSPLIB are not strictly random. This means that they cannot "guarantee that the topology is a random selection from the space of all possible networks which satisfy the specified input parameters" (Herroelen 2005, p. 422). The most random networks are generated by ProGen/max or RanGen project problem generators (Demeulemeester et al. 2003). Project problem generators create a desirable number of networks with the user predefined characteristics. However, comparing those two generators, RanGen has more advantages when compared to the other generators (Demeulemeester et al. 2003):

- RanGen uses complexity measures, which have been shown to have a strong relationship to the hardness of different scheduling problems;
- RanGen is straightforward as it does not use arc weights, and can generate networks with small values of complexity measure (order strength);
- RanGen networks are strictly random.

On the basis of this literature review of project scheduling problem sets, and analysis of suitability for the research being performed, the RanGen software was selected for the generation of project schedules in this research.

When applying RanGen, several parameters have to be chosen to generate a network. They are divided into two groups: network topology related parameters, and resource related parameters.

1. Topology parameters:
    a) Complexity index (CI);
    b) Order strength (OS).
2. Resource parameters:
    a) Resource requirements:
        - resource factor (RF);

- resource use (RU).

b) Resource demand:

- resource constrainedness (RC);
- resource strength (RS).

Complexity index (CI) serves as a measure of network complexity, and is calculated by the generator itself.

The parameter of network topology, which has to be entered into the generator, is order strength (OS). OS is defined by Demeulemeester et al. (2003, p. 19) as “the number of precedence relations (including the transitive ones but not including the arcs connecting the dummy start or end activity) divided by the theoretical maximum number of precedence relations”. The higher the OS, the higher is the density of the network. OS value ranges from 0 to 1. For the first set of simulations, the value of 0.3 is selected. The performed experiment shows, that selecting the value of OS = 0.3 gives the values of CI within the range of 0 to 5 (Demeulemeester et al. 2003). Changing the value of order strength would lead to different values of complexity index. In this way a range of easy and hard project networks could be created.

Defining the resource parameters, the selection between resource factor (RF) and resource use (RU) has to be made, as well as the selection between resource constrainedness (RC) and resource strength (RS).

RF shows the “average portion of resource types requested per activity” (Demeulemeester et al. 2003, p. 34). However, when applying RF in RanGen there is the possibility that some activities will be generated without any resource requirement. To ensure that each activity will need at least one resource type, another parameter, measuring resource density, is applied – RU. Resource use RU is calculated as by Equation 3.1 (Demeulemeester et al. 2003).

$$RU_i = \sum_{k=1}^{K} \begin{cases} 1, & if\ r_{ik} > 0,\ \ i = 1, \dots, n \\ 0, & otherwise \end{cases} \tag{3.1}$$

where n – number of activities;

K – number of resource types;

r_{ik} – amount of resource type k required by activity i.

The following equation ensures that each activity uses at least one resource type:

$$RU_i = RU \tag{3.2}$$

where RU is a positive constant.

To ensure that each activity would need at least one resource type, the RU was selected as the input parameter instead of RF for this research. Resource buffers are analysed in this research, therefore it was important that the value of RU ranges from 0 to the number of available resource types. As a random number of 6 resource types is assumed in this research, the value of RU has to be selected from the range of 0 to 6. For the first set of simulations, the value of 2 has been selected. This means that every activity in the network will require two types of resources.

To specify the resource demand, either the parameter of resource strength (RS) or the resource constrainedness (RC) has to be entered in RanGen. On the basis of the description in Demeulemeester et al. (2003), the RC parameter has been selected for the research. RS has the disadvantage of not being a “pure measure” of resource availability as it incorporates the information about the precedence structure of the network. Therefore resource constrainedness RC was selected and calculated by the equation (Patterson 1976 cited in Demeulemeester et al. 2003):

$$RC_k = \frac{\bar{r}_k}{a_k} \tag{3.3}$$

Where a_k – total availability of renewable resource type k;

$\bar{r}_k$ – average quantity of resource type k demanded when required by an activity:

$$\bar{r}_k = \sum_{i=1}^{n} r_{ik} / \sum_{i=1}^{n} \{1, if\ r_{ik} > 0; 0\ otherwise\} \tag{3.4}$$

The RC value for the simulations in this research was chosen to be 0.5, which means that the “average usage of an activity that needs a certain resource type equals half the availability of that type” (Van de Vonder et al. 2006, p. 223).

The above described values of parameters were chosen for the initial simulation. It was planned to change the parameters, to compare the results of projects with different network parameters, and to define how the network parameters influence the optimum size of the resource buffer.

3.3.6. Independent input parameters

The independent input parameter, whose influence on performance measures was evaluated, was the size of resource buffer.

The size of resource buffer was expressed in the percentage of time the resource was planned to work without interruptions before starting the work on a protectable critical activity. Protectable critical activity is the critical chain activity, which is started by a resource other than the preceding critical activity. For example, if critical activity III is performed by resource B and resource C, and the preceding critical activity II is performed by resources A and C, the protectable critical chain activity is III and the resource buffer is needed for resource B.

The size of resource buffer was expressed in the percentage of time the resource was planned to work without interruptions before starting the work on a protectable critical activity. Percentages of 10%, 30% and 50% were used in this research. For example, resource B on the critical activity III needs to be protected by a resource buffer. Before the work on the critical activity, resource B was planned to work for 10 days on another non-critical activity. Therefore, in the case of the 10% resource buffer, the size of it would be 1 day; in case of the 30% resource buffer, it would be 3 days; and in the case of the 50% resource buffer, the size would be 5 days.

3.3.7. Simulation of project execution

3.3.7.1. Generating random activity durations

The analysis of the developed hypotheses requires simulation of project implementation. This means that the activity durations during project execution should be generated randomly. An assumption was made that activity durations change independently from each other.

A number of researchers use lognormal distribution to simulate activity durations (Demeulemeester and Herroelen 2002; Tukel et al. 2006). This right skewed distribution enables the variation of the standard deviations of the activity durations, without changing the mean values of durations.

It is known from statistics that lognormal distribution is the continuous probability distribution of a random variable whose logarithm is normally distributed. Therefore, if X is a random variable with normal distribution, then Y=exp(X) duration Y is lognormal. In order to be able to generate random numbers for a lognormal distribution, we must first know the values of the mean and standard deviation parameters.

When X is a normal random variable with mean μ and standard deviation σ, the mean for Y is:

$$\mu_y = e^{(\mu+\frac{1}{2}\sigma^2)} \qquad (3.5)$$

As the mean value of activity duration from the problem data set (d_i) should remain the same, the following equation might be derived:

$$d_i = \mu_y = e^{(\mu + \frac{1}{2}\sigma^2)} \quad (3.6)$$

As a normal random variable X with mean μ and σ should be generated, the mean can be derived from equation 3.6 and calculated by equation 3.7.

$$\mu = \ln(d_i) - \frac{1}{2}\sigma^2 \quad (3.7)$$

When varying different values of standard deviation σ, different degrees of uncertainty in activity durations were modelled and random activity durations generated. This was performed by EasyFit software. The input parameters are the selected σ values and μ as the duration of activity from a schedule.

The initial restriction of variable σ values was made to $0< \sigma<1$, as the lognormal distribution changes to exponential when $\sigma>1$ (Fallah et al. 2010). When $\sigma = 0$, the activity durations become fixed. A case without variation no longer represents a realistic case in the practical project management environment. The upper bound $\sigma = 0.5$ is restricted following the research performed by Fallah et al. (2010). They demonstrated that having values of $\sigma > 0.5$ leads to the high probability of ending the project activity in the time range larger than twice the median activity duration, which is unacceptable and should be avoided. Therefore, the values of σ are restricted to:

$$0.1 < \sigma < 0.5 \tag{3.8}$$

Three values of σ have been selected from the restricted range (3.8) for simulations: 0.1; 0.3; 0.5. These values represent different degrees of uncertainty:

- 0.1 low uncertainty,
- 0.3 medium uncertainty,
- 0.5 high uncertainty.

The availability of resources is assumed to be fixed and the data is given by the generated project network. An assumption was made that the activities in the network were independent.

3.3.7.2. Goodness of fit tests

After the random activity durations are generated, they have to be checked by goodness of fit tests. There are three tests available on the EasyFit software. These tests are used to check if the generated random numbers come from the assumed distributions. The methodology of these tests is beyond the scope of this research, so a detailed explanation is not provided. The application of the tests was performed automatically by EasyFit software, and the results provided by EasyFit were analysed. An example of the goodness of fit tests output is presented in Table 3.2.

Lognormal [#41]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	100 0.067445 0.727353 14				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.10563	0.12067	0.13403	0.14987	0.16081
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size Statistic Rank	100 0.264872 18				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.37491	1.92862	2.50176	3.2892	3.90742
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	6 2.96016 0.813831 24				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	8.55806	10.6446	12.5916	15.0332	16.8119
Reject?	No	No	No	No	No

Table 3.2. Goodness of fit tests

The data sets that were rejected by at least one of the tests for not following lognormal distribution were not used for the simulations, and new random numbers were generated.

3.3.7.3. Project updates

During the simulation of project execution, the schedule updates were carried according to the traditional CCPM methodology, following the planned schedule. Priority was given to critical chain tasks and they were started as soon as possible. The non-critical tasks were started according to the baseline schedule, i.e. as late as possible, taking into account resource availabilities, feeding and resource buffers. An assumption was made that the activities could not be split.

3.4. Software used for research

A detailed analysis of commercially available software products was performed. One of the reasons for the investigation was to uncover the differences between CCPM theory and practice. An article has been written based on this research, and is presented in the Appendix A of this thesis. The second reason to perform the analysis was to find the most suitable software for the planned simulations. Initially, Agile CC was defined as the most appropriate as it was the only software using resource buffers. Unfortunately, after the full version of the software was purchased, it was realised that the term “resource buffer” is misleading, as instead of a single project environment, the resource buffer in Agile CC was applied only in the cases of multi-projects, and should actually be called a capacity buffer according to CCPM terminology. This left the research without a software application in which schedules with automatically inserted resource buffers could be analysed. Nevertheless, it was decided that the simulations should be performed with the software already purchased. In order to insert resource buffers, the additional activity was added manually to represent the resource buffer. The adjustments during project execution were also made manually.

For generating random activity durations, EasyFit software was used. The generation of random networks was performed by the already described RanGen. The visual presentation of RanGen generated networks was achieved with another software called Rescon. Rescon transforms the generated numbers from RanGen into the visual network. Other calculations were performed with the help of Microsoft Excel software.

Figure 3.2 presents an illustrative example of the network, generated by the RanGen software and visualised by Rescon software. The first row in a box shows the number and the duration of an activity. The second row in a box shows the quantity of the resource (first/second/third/fourth/fifth/sixth) needed for work on the activity. The lines between the boxes represent interdependencies between activities. For example, activity No. 2 takes 8 days and is performed by resource No. 1 (quantity 7) and resource No. 3 (quantity 1). The activity 2 can be started when activity 1 is finished. The activity 2 is a predecessor of activities No. 4 and No. 8. It should be noted that Rescon does not show the dummy links in a network. Therefore activities 9 and 10 seem to be unlinked to the other activities in the schedule. When the network is entered into the Agile CC, the links between the activities 9, 10 and the end of project are added. The networks visualised by Rescon of other projects are presented in Appendix B.

The generated project network was then manually entered into the Agile CC. Figure 3.3 demonstrates an example of a project schedule, solved by Agile CC.

Feeding buffers were added automatically by Agile CC, and resources buffers were added manually. The total availability of any type of resource was 10, so if the resource requirement for a particular activity was 7, the resource requirement was expressed as 70%. The generated durations by RanGen were multiplied by 10 when entering into Agile CC. RanGen generates activities with relatively short durations. The networks generated for this research had activities with durations ranging from 1 to 9 days. If the activity durations were not multiplied 10, the durations of resource buffers could be hours short and could not be approximated to days. This would complicate the scheduling and analysis of the projects in this research. Therefore, the decision was made to make adjustments and to increase all durations ten times. Another option would be to transform all durations into hours without actually changing the generated durations.

The software used for research is available online: Agile CC (http://www.adepttracker.com/agilecc/), Rescon (http://feb.kuleuven.be/rescon/), RanGen (http://www.projectmanagement.ugent.be/?q=research/data/RanGen), Easyfit (http://www.mathwave.com/easyfit-distribution-fitting.html).

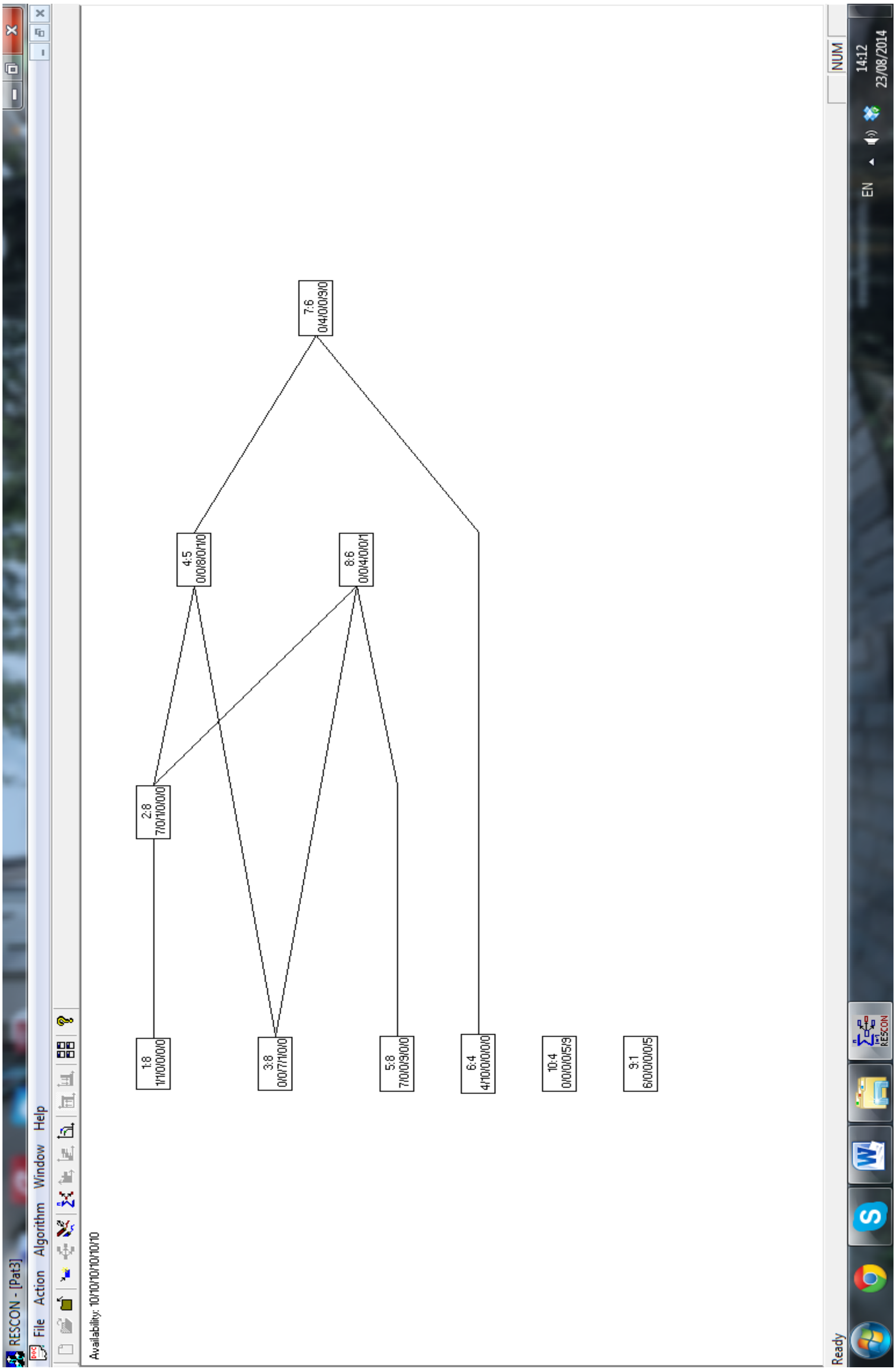

Fig. 3.2. Project network, generated by RanGen

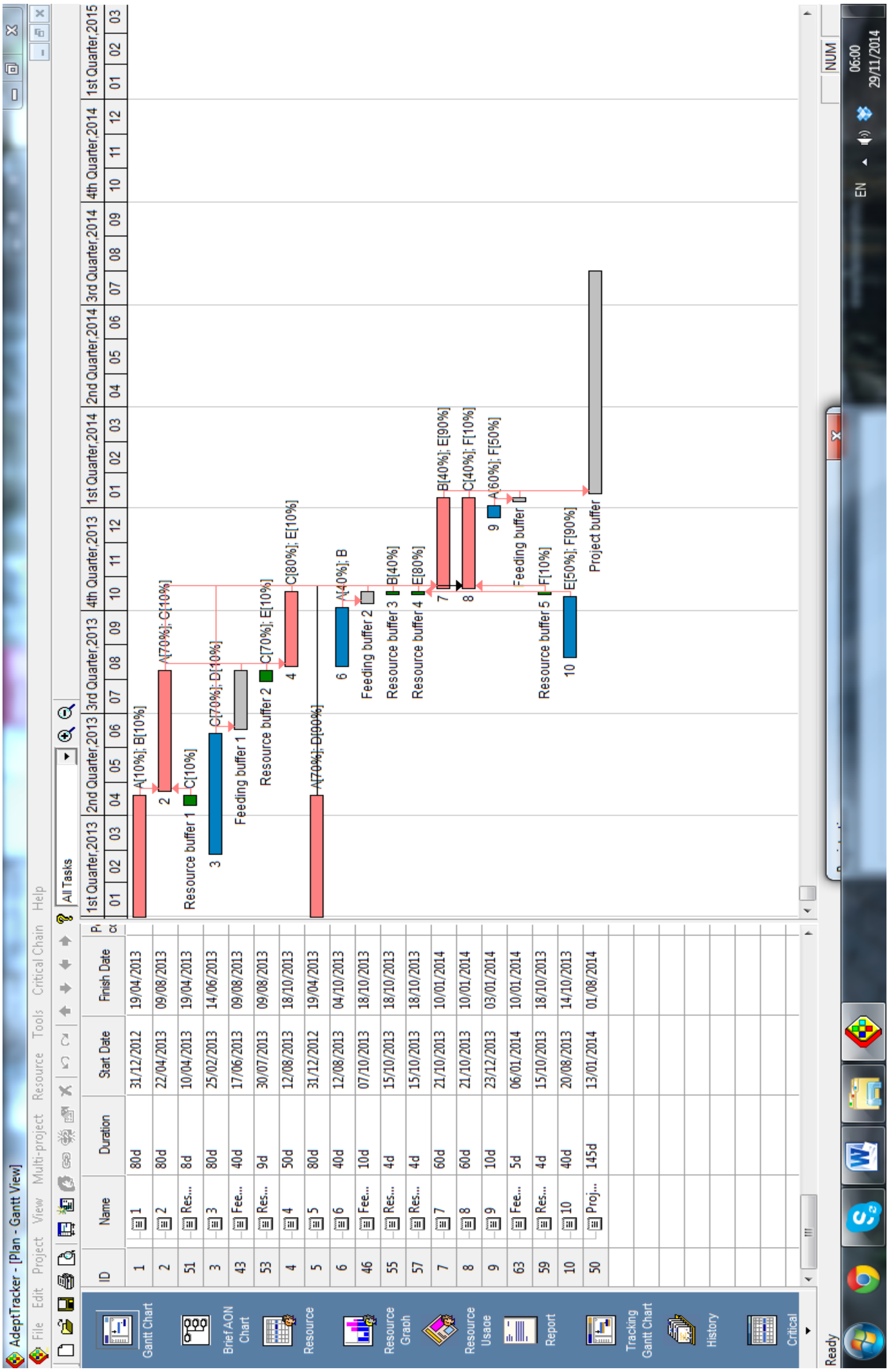

Fig. 3.3.Project schedule in Agile CC

3.5. Simulation algorithm

The simulation in this research was performed by keeping this sequence:

1. Generate random networks by RanGen. The input parameters were: OS 0.3, RU 2, RC 0.5, number of activities in a project 10, number of generated networks 3, number of resource types 6 (see Chapter 3.3.5).

2. Enter the generated network information to Agile CC software.

3. Insert FB and PB and solve resource constrained project scheduling problems using Agile CC software.

4. Record the finish date of the planned project schedule.

5. Manually insert RB.

6. Generate random activity durations using Easyfit software. Microsoft Excel was used to calculate values of μ varying the values of σ as 0.1; 0.3 and 0.5. For each value of μ, 100 of random activity durations were generated.

7. Simulate project execution by changing activity durations, i.e. inserting the randomly generated ones into Agile CC.

8. Calculate new project duration.

9. Record the end date of the project and compare it to the planned project deadline.

10. Repeat the steps for different percentages of buffer size and different uncertainties.

14. Summarize and analyse results.

15. Validate simulation results.

The step 14 is presented in Chapter 4, step 15 is addressed in Chapter 5.6.

A more generalised algorithm of simulation for a specific project is shown in the Figure 3.4.

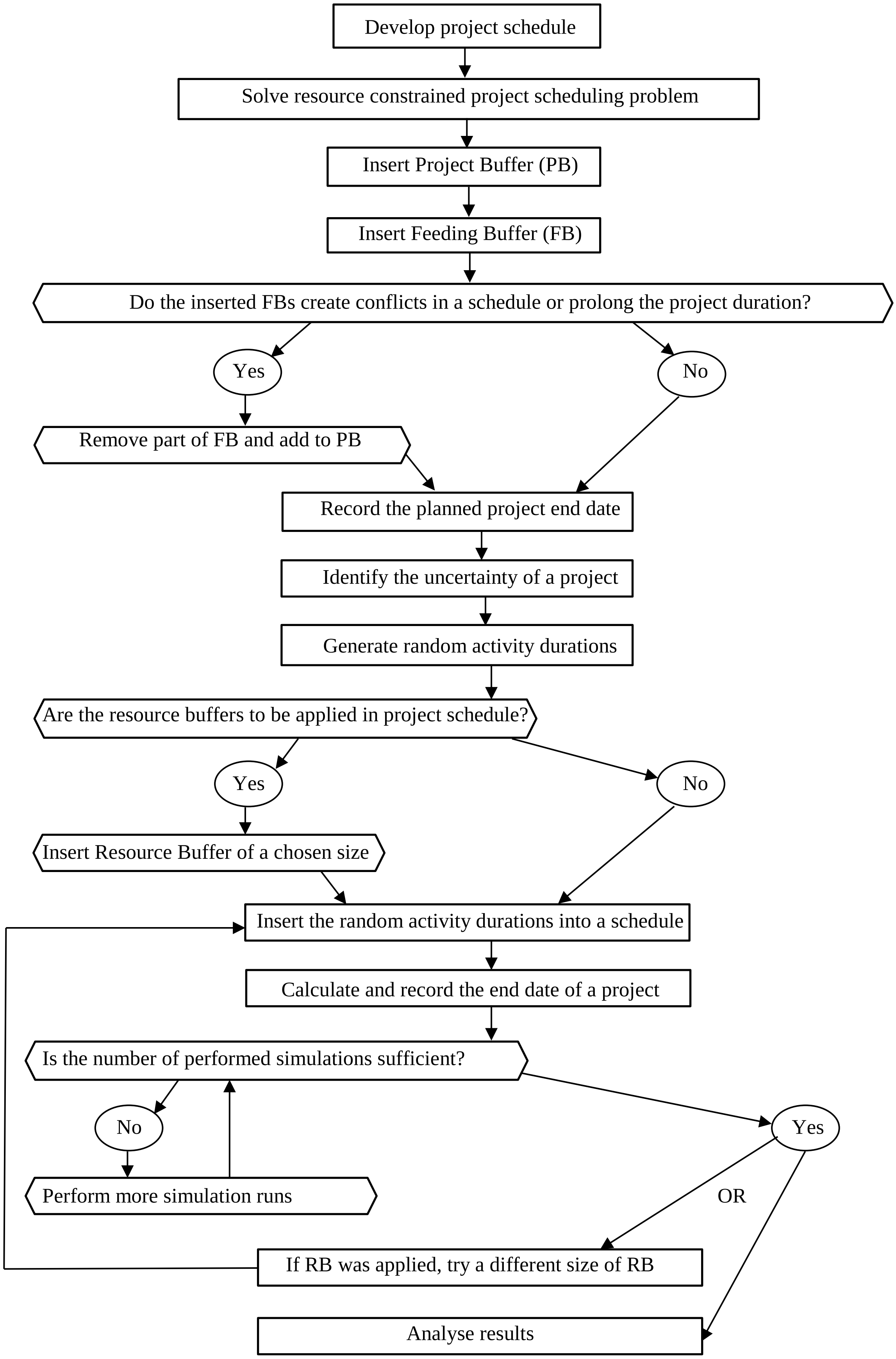

Fig. 3.4. Simulation algorithm

3.6. Summary

The simulation design has been described in Chapter 3. Minimum project duration was selected as the objective function. Three hypotheses have been developed, enabling the evaluation of whether the application of resource buffers could help to reduce duration, and to determine the buffer size depending on the level of uncertainty. The variable parameters are buffer size and uncertain activity durations, generated according to lognormal distribution by the EasyFit software. The assumption of independent activity durations was made, and the activities could not be split. The most advanced RanGen project instances generator was used to generate random networks, with the initial values of order strength equal to 0.3, resource constrainedness value equal to 0.5, and resource use value equal to 2. Three networks, each having 10 activities, and 6 types of resources were generated. Buffer sizes were selected as percentages of 10, 30, and 50% of the time that the resource was working without interruptions before starting work on a critical protectable activity. The resource constrained project scheduling problem was solved by the algorithm encoded in CCPM software – Agile CC. The sizes of FB and PB were calculated by the 50% rule.

CHAPTER 4. SIMULATION RESULTS

4.1. Analysis of simulation output data

4.1.1. Fitting statistical distribution

The first step of the simulation output analysis was to find a statistical distribution which could describe the simulation results well. Applying the wrong distribution could lead to mistakes in further calculations. Well fitted distribution helps to decide which methods to use for statistical analysis: parametric or non-parametric methods. Fitting of distribution also provides information needed to determine which measure of central location to apply in analysis: mean, median or mode.

The fitting of statistical distributions was performed using EasyFit software. First of all, the graphical form was evaluated and the most popular distributions were tried to fit (normal, lognormal, exponential, etc.). Next, the Kolmogorov Smirnov, Anderson Darling and Chi-Squared goodness of fit tests were performed to check if the analysed distribution should not be rejected. These tests are described in Chapter 3, and are used in the same way as in Chapter 4.

The most popular methods used in statistics are based on the analysis of data that follows normal distribution. Indeed, other distributions can be often approximated to normal distribution because of the central limit theorem: having a large number of independent observations, the average of observed results follows normal distribution (Anderson et al, 2013). However, this is not always the case. As the input data in this research was distributed log-normally, increasing the number of simulation iterations could still lead to skewed output data distributions. In this case the parametric methods cannot be used for analysis, as they assume the normal distribution of data.

Table 4.1 shows fitted statistical distributions for all projects. Normal distribution was valid for only one of the projects (Project No. 2, uncertainty 0.1).

	No buffer	10% RB	30%RB	50%RB
0.1 uncertainty				
Project No.1	Right skewed	Right skewed	Right skewed	Right skewed
Project No.2	Normal	Normal	Normal	Normal
Project No.3	Lognormal	Lognormal	Lognormal	Lognormal
0.3 uncertainty				
Project No.1	Right skewed	Right skewed	Right skewed	Right skewed
Project No.2	Lognormal	Lognormal	Lognormal	Lognormal
Project No.3	Lognormal	Lognormal	Right skewed	Right skewed
0.5 uncertainty				
Project No.1	Right skewed	Right skewed	Right skewed	Right skewed
Project No.2	Lognormal	Lognormal	Right skewed	Right skewed
Project No.3	Right skewed	Lognormal	Lognormal	Right skewed

Table 4.1. Fitted distributions for simulation output data

The graphical shape of the cumulative distribution function of other projects was similar to the widely used lognormal distribution. The log of lognormal distribution is normally distributed. So if the data follows lognormal distribution, its log values can be analysed and the same parametric analysis methods can be applied as for normal distribution. Therefore lognormal distribution was chosen next for fitting.

Lognormal distribution was a good fit for some of the data (Project 3, uncertainty 0.1; Project 2, uncertainty 0.3; Table 4.1). However, the other data did not follow lognormal distribution, as its log was not normally distributed and it failed all or some of the Kolmogorov Smirnov, Anderson Darling or Chi-Squared tests.

The next step was to try fitting other distributions. They were arranged by the goodness of fit option in EasyFit software. In order to compare groups of results with each other, the same shape of distribution should be applied to each group. Unfortunately, this was impossible as simulation results with different sizes of resource buffers were a good fit with different distributions. The same distributions were rejected by one or all of the goodness of fit tests. For this reason the distribution shape was determined, just as right-skewed and distribution free nonparametric methods were chosen for statistical analysis.

The decision was made to use nonparametric statistical tests, not only for right skewed distributions, but also for normal and lognormal ones. Using nonparametric methods for all the data in this research simplified statistical analysis. Many researchers try to transform their data to fit normal distribution, so that parametric tests can be used (Conover and Iman 1981). However, "in many cases where a nonparametric test as well as a parametric method can be applied, the nonparametric method is almost as good or almost as powerful as the parametric method" (Williams 2006; p. 756).

4.1.2. Central location of data

The simulation output results were skewed to the right and not distributed normally. Consequently, the mean was not the most often occurring value. The resistant to extreme values parameter – the median – was chosen as a measure of central location. In case of the skewed distribution, the median is the parameter that splits the results in half, i.e. half of the results are the median and above, and the other half are below the median.

4.1.3. Number of simulation iterations

The question of how many simulation iterations to run is especially important when simulation is performed manually. Too much iteration might lead to excessive time needed to perform simulations and analyse the data, while too few iterations might lead to incorrect results. Researchers usually use the following ways to decide on the number of simulation iterations (or sample sizes) (Robinson 2004):

- They just choose a random number. In the field of project management, a different number of simulation runs is without any justification. For example, Tukel et al. (2006) repeat simulation 100 times, Cohen et al. (2004) replicate each simulation 50 times, while Lambrechts et al. (2010) perform 1000 iterations;

- They apply graphical method. A cumulative mean or median shows that it almost does not change after a certain number of simulation iterations;
- They calculate confidence levels, which show the true value of the median not only for the simulation iterations performed, but for the whole population. The desired precision is defined and then it is checked if the analysed data satisfies the set precision.

Initially, the first method was used. For the start, 100 simulation iterations were performed for each project under different uncertainties and different sizes of resource buffers.

With the results from these 100 simulation iterations, the moving cumulative median was plotted graphically, which in most cases showed to be settled (for example, Figure 4.1). For the graphical presentation of cumulative moving medians of other projects see Appendix C.

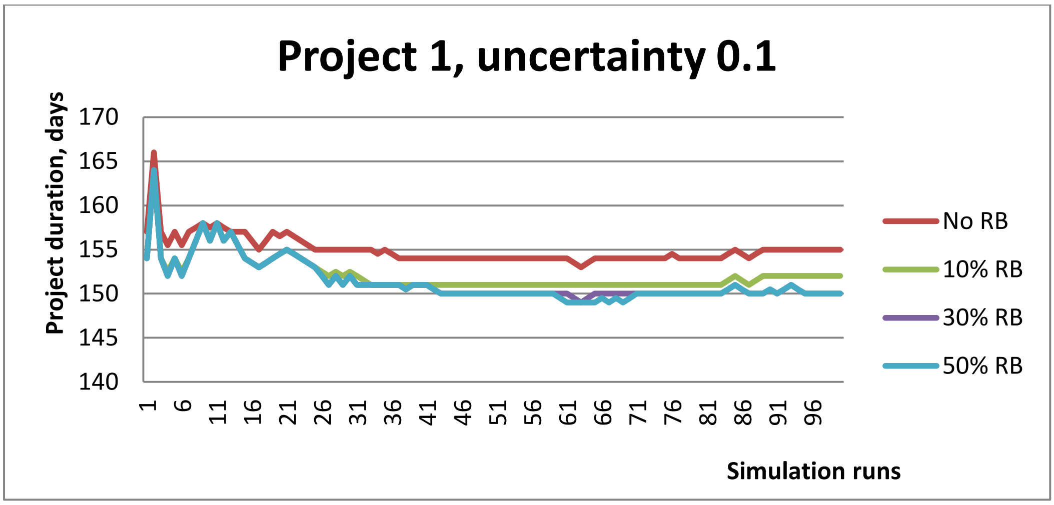

Fig. 4.1. Cumulative median values of Project No. 1 duration under 0.1 uncertainty

Finally, the confidence levels were calculated. As the number of simulation iterations was >20, the approximated nonparametric formulae were used to compute confidence intervals (Schwartz 2011):

$$R_{lower} = n(0.5) - z\sqrt{n(0.5)(1-0.5)} \tag{4.1}$$

$$R_{lower} = n(0.5) + z\sqrt{n(0.5)(1-0.5)} \tag{4.2}$$

The confidence interval is Y [R_{lower}] to Y [R_{upper}].

The confidence level for this research was set to 95%, which is the most often used confidence level in research (Agresti and Caffo 2000). The *z* value for 95% confidence is 1.96. This leads to R_{lower}= 40 and R_{upper}= 60. Thus the confidence interval for each project in this research is between the 40^{th} and the 60^{th} simulation iterations, and the results arranged in increasing order.

Table 4.2 provides summary information for median confidence intervals of all projects durations. It shows, that the medians of some projects have very wide confidence intervals, for example Project 2, uncertainty 0.5. The cumulative median values for the same project could also benefit from further simulations, as the values do not seem to settle completely (Figure 4.2).

	No buffer	10% RB	30%RB	50%RB
0.1 uncertainty				
Project No.1	153-157	150-154	149-153	148-153
Project No.2	282-289	280-289	280-289	280-289
Project No.3	276-283	271-279	268-275	268-275
0.3 uncertainty				
Project No.1	161-165	159-162	156-161	153-160
Project No.2	294-309	290-306	290-303	288-302
Project No.3	287-299	275-291	262-280	258-274
0.5 uncertainty				
Project No.1	171-185	168-184	165-182	164-182
Project No.2	308-352	307-352	307-347	307-342
Project No.3	306-331	297-329	284-310	276-303

Table 4.2. Confidence intervals for the project duration median

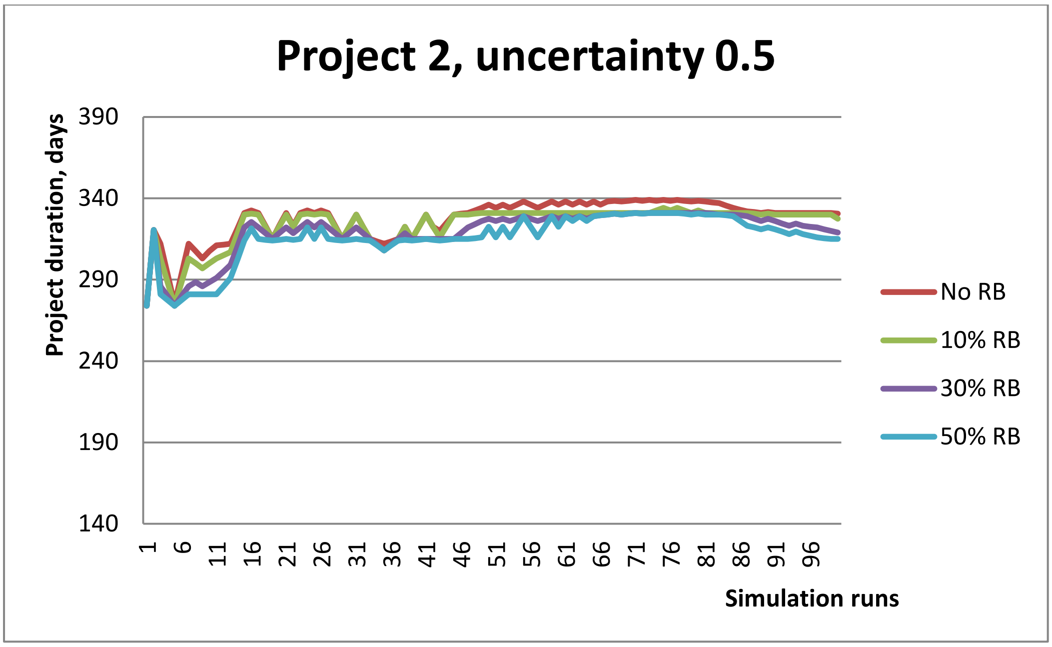

Fig. 4.2. Cumulative median values of Project No. 2 duration under 0.5 uncertainty

However, increasing the number of iterations for this project would not change the recommendations and conclusions of this research. In addition, in this research more emphasis has been placed not on the median value itself, but on the difference between median values of different populations.

Based on this information, 100 of simulation iterations were considered enough for further analysis.

4.1.4. Differences between projects

The obtained results of simulations showed that applying resource buffers leads to shorter project durations. This is further discussed in the following sections (4.2-4.4). The shorter project durations can be seen in the figures showing cumulative median values (Appendix C). In addition, different tests may be employed to check whether a significant difference exists among the population durations of projects, examine that the different median values appear not due to a chance.

4.1.4.1. Kruskal-Wallis test

The nonparametric Kruskal-Wallis test is used to check whether more than two populations are identical. The hypothesis are:

H_0: All populations are identical

H_a: Not all populations are identical

The test statistic is calculated by equation (Williams 2006; p. 781):

$$W = \left[\frac{12}{n_T(n_T+1)}\sum_{i=1}^{k}\frac{R_i^2}{n_i}\right] - 3(n_T + 1) \qquad (4.3)$$

Where k = the number of populations

n_i= the number of items in sample *i*

$n_T=\sum n_i$= total number of items in all samples

R_i= sum of the ranks for sample *i*

When the W value is calculated, the chi-square distribution table or Microsoft Excel software can be used to find the *p*-value. The *p*-value is a probability, which is a basis to reject (not reject) a hypothesis under a certain level of significance. The rejection rule for the question in this chapter is:

$$\text{Reject } H_0 \text{ if } p\text{- value} \leq \alpha$$

The level of significance for this research was set 0.05. The *p*- value for the Kruskal-Wallis test was calculated and it was 0.0000 for all the projects under different uncertainties and different sizes of resource buffers. This rejects the hypothesis H_0 and shows that the difference between projects is statistically significant and not all populations are identical.

4.1.4.2. Wilcoxon Signed Rank test

The Kruskal Wallis test rejected the hypothesis that all populations are identical. The next nonparametric test was used to check whether the significant difference exists between projects, comparing two of them separately.

The hypothesis are:

H_0: Two populations are identical

H_a: Two populations are not identical

Sampling distribution of *T* for identical populations (Williams, 2006; p. 767):

Mean: $$\mu_T = 0 \quad (4.4)$$

Standard deviation: $$\sigma_T = \sqrt{\frac{n(n+1)(2n+1)}{6}} \quad (4.5)$$

Here *T* is the sum of signed rank values. First of all, the differences between the values of two populations are calculated, the zero differences discarded, and the data is ranked. The ranked values are assigned their original difference sign (plus or minus). When the mean and standard deviation values are calculated, the test statistic can be found (Williams 2006, p. 767):

$$z = \frac{T - \mu_T}{\sigma_T} \quad (4.6)$$

The procedure of finding *p*-value and comparing it to the level of significance α is repeated in the same way as for the Kruskal-Wallis test. The same rule for rejecting hypothesis is valid:

Reject H_0 if p- value $\leq \alpha$

Following the described procedure, the mean, standard deviation, test statistic, and p-values were calculated.

The p-value for Project 2, uncertainty 0.1, comparing projects with 30% resource buffer and 50% resource buffer, was more than the set level of significance, i.e. p-value $= 0.5 > \alpha = 0.05$. Exactly the same results were obtained for Project 3, uncertainty 0.1, comparing projects with a 30% resource buffer and 50% resource buffer. For these two cases the hypothesis that two populations are identical could not be rejected.

The p-value for all the other projects under different uncertainties and with different sizes of resource buffers was 0.0000. Therefore the hypothesis H_0 was rejected. The projects are not identical, and there are significant statistical differences between them.

Having these results for identical and not identical projects, it might be tempting to conclude that there is no reason to apply 50% resource buffers to projects under low uncertainty. The 50% resource buffer did not lead to any changes in project durations compared to the 30% resource buffer under uncertainty of 0.1. There was no significant statistical difference between them. However, this was the case for Project 2 and Project 3, but not for Project 1. The results of all the projects and differences between them are discussed in more detail in the following sections (4.2-4.4).

4.1.5. Visual representation of results

The results have been presented in the table format as well as box-and-whisker plots. The box-and-whisker plots were chosen for display as they do not clutter with too many additional numbers, but provide the most important information: median, minimum and maximum values, lower and upper quartiles. It is easier to compare different projects with a large amount of data in one graph.

Figure 4.3 provides the explanation of box-and-whisker plot.

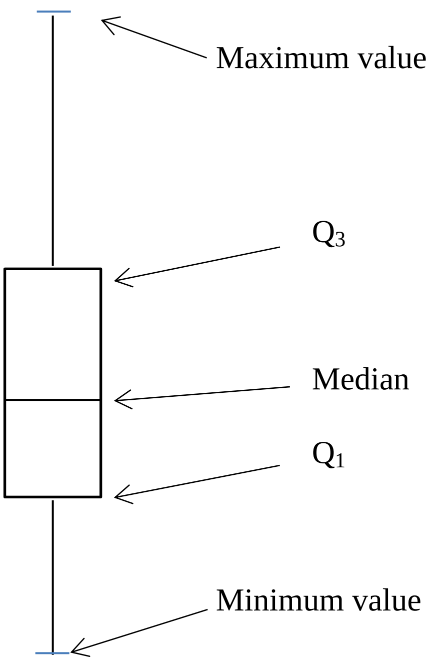

Fig. 4.3. Box-and-whisker plot

Q_1 is a lower quartile of the data, which is 25% percentile. Q_3 is an upper quartile, which is 75% percentile. The width of the box shows the interquartile range.

The exact values of median, quartiles, minimum and maximum values are shown in the tables below the box-and whisker plots.

4.2. <u>Low uncertainty projects</u>

4.2.1. Project No. 1

The summary of simulation results for Project 1 under low uncertainty 0.1 is presented in Figure 4.4. It is easy to see that insertion of larger resource buffers in a project schedule decreases the values of both the median, and minimum durations.

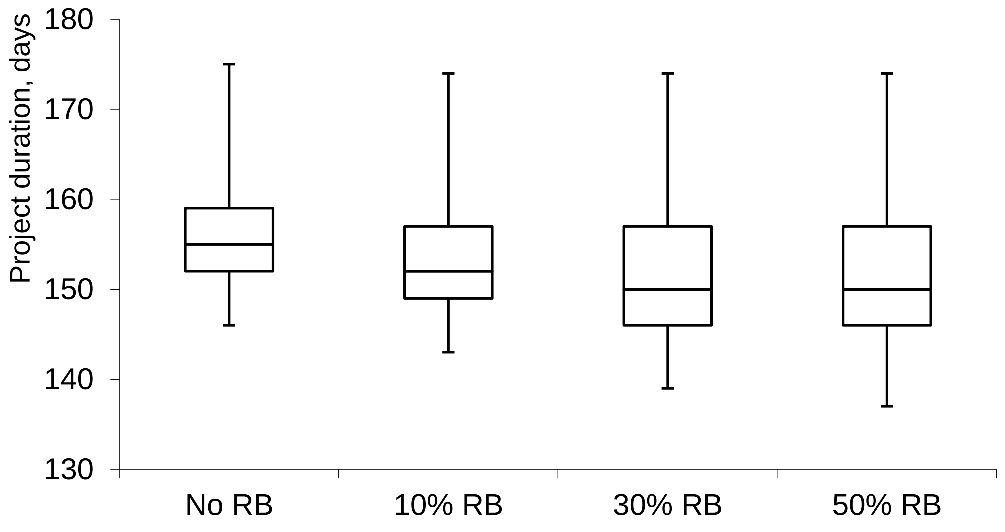

Fig. 4.4. Box-and whisker plot for Project 1, uncertainty 0.1

Visually, the biggest differences in median, min and max values appear between projects with no resource buffer and a 10% resource buffer. A slightly smaller difference appears between the 10% and 30% resource buffers, and another small difference in the min value between the 30% and 50% resource buffer. This is confirmed by the exact values of these parameters in Table 4.3.

	No RB	10% RB	30% RB	50% RB
Median	155	152	150	150
Min	146	143	139	137
Max	175	174	174	174
Q_1	152	149	146	146
Q_3	159	157	157	157

Table 4.3. Median, minimum, maximum and quartile values of Project 1 duration, uncertainty 0.1

Based on this information, one could decide that a 50% resource buffer should not be applied to this project, as the median, interquartile range (11), 25% (146) and 75% (157) quartiles have the same values for 30% and 50% RB. However, analysing additional information in Table 4.4, one can see that 18% of projects with 50% RB had shorter duration compared to the project with 30% RB. The percentage is quite small, and in most cases the 50% resource buffer would not be recommended.

	No RB	10% RB	30% RB	50% RB
Project completed before deadline	100%	100%	100%	100%
Project completed sooner		74% (compared to the project duration with No RB)	49% (compared to the project duration with 10% RB)	18% (compared to the project duration with 30% RB)

Table 4.4. Completion on time and shortening of Project 1 duration, uncertainty 0.1

However, the selection of resource buffer size depends not only on the duration of the project, but the cost of additional resources or additional time for resource buffers, as well as the cost of finishing later or the benefits of finishing earlier. These questions are discussed in Chapter 5. Other factors influence decisions too, such as the importance of finishing on time, net present value, cash flows, resource storage on site, stakeholders, and many others. The other factors are beyond scope of this work.

For this particular project all of the resource buffer sizes could be beneficial depending on the other factors.

4.2.2. Project No. 2

The results of Project 2 simulation are presented in Figure 4.5. Visually the values of all medians, maximum values and quartiles seem the same. Only the minimum value was different for cases where there was no resource buffer, and where the 10% resource buffer was applied.

Analysis of the numbers in Table 4.5 shows that there is a change in the value of the median by 1 day when 10% resource buffer is applied instead of no resource buffer. The minimum value changes by 2 days, while the upper quartile changes by 1 day.

Additional information on the project in Table 4.6 confirms that there is no change at all between projects with a 30% resource buffer and a 50% resource buffer. In fact, the percentage of shortening project duration with a 30% resource buffer is also quite low.

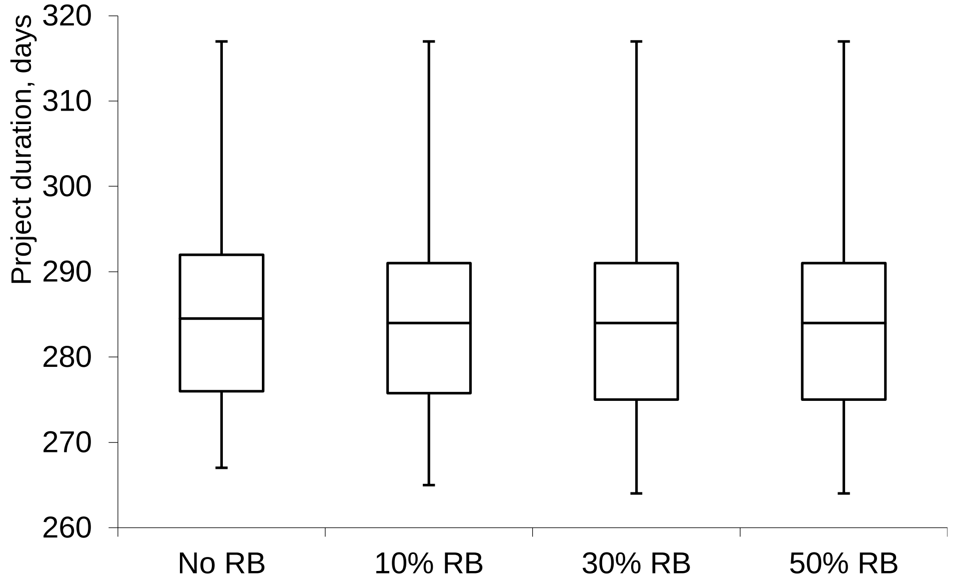

Fig. 4.5. Box-and whisker plot for Project 2, uncertainty 0.1

	No RB	10% RB	30% RB	50% RB
Median	285	284	284	284
Min	267	265	264	264
Max	317	317	317	317
Q_1	276	276	275	275
Q_3	292	291	291	291

Table 4.5. Median, minimum, maximum and quartile values of Project 2 duration, uncertainty 0.1

	No RB	10% RB	30% RB	50% RB
Project completed before deadline	100%	100%	100%	100%
Project completed sooner		32% (compared to the project duration with No RB)	11% (compared to the project duration with 10% RB)	0% (compared to the project duration with 30% RB)

Table 4.6. Completion on time and shortening of Project 2 duration, uncertainty 0.1

The simulation results for this project would obviously support the decision not to apply the 50% resource buffer. However, the 30% resource buffer is also questionable, as the median, upper quartile and maximum value do not change, and the minimum value and the lower quartile change only by 1 day. In addition, the percentage of shortening project duration when the 30% resource buffer is used is also very low. Nevertheless, the 30% resource buffer could still be applied for projects with low additional resource or time cost for resource buffer and high benefits of finishing earlier.

4.2.3 Project No. 3

The graphical representation of results for Project 3 under low uncertainty again shows no difference between projects with 30% and 50% resource buffers, as for Project 2 (Figures 4.5 and 4.6). The biggest difference can be seen between projects with no resource buffer and a 10% resource buffer, a slightly smaller between 10% and 30% resource buffer projects. There is a large change in the minimum value between no resource buffer and 10% resource buffer, as well as 10% and 30% resource buffer projects.

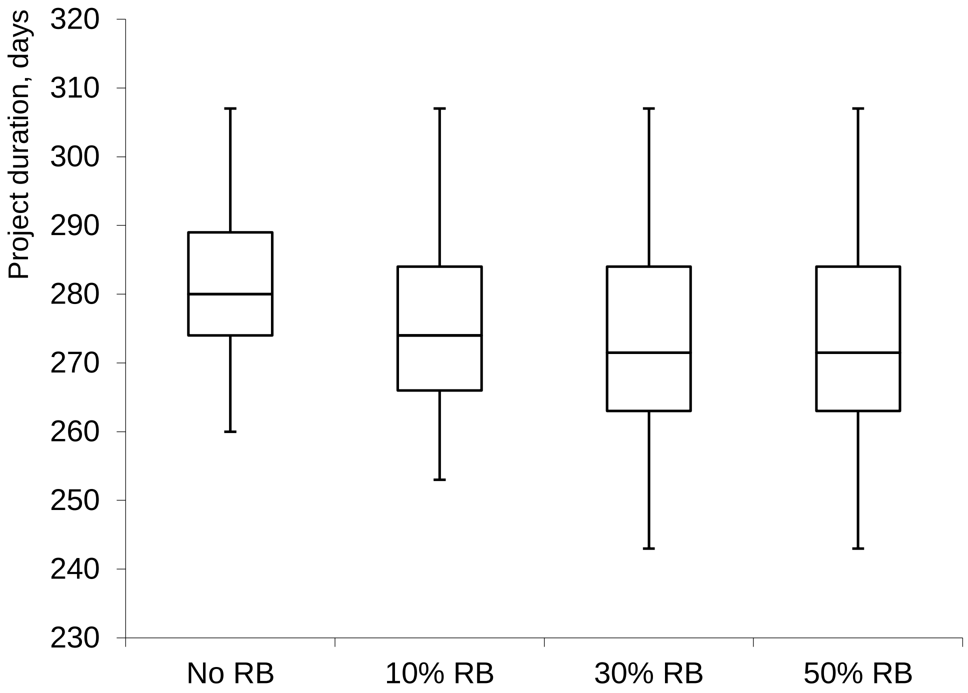

Fig. 4.6. Box-and whisker plot for Project 3, uncertainty 0.1

The values in Table 4.7 indicate a much bigger change (6 days) in the median value between a project without a resource buffer and 10% resource buffer in comparison to project 1 and 2, where the changes were 3 and 1 correspondingly. A large change in the minimum value and 60% of the shortened projects also confirm that project duration decreased often, and by relatively high number of days. Even a 30% resource buffer led to a shorter duration of 1/3 of project iterations.

	No RB	10% RB	30% RB	50% RB
Median	280	274	272	272
Min	260	253	243	243
Max	307	307	307	307
Q_1	274	266	263	263
Q_3	289	284	284	284

Table 4.7. Median, minimum, maximum and quartile values of Project 3 duration, uncertainty 0.1

	No RB	10% RB	30% RB	50% RB
Project completed before deadline	100%	100%	100%	100%
Project completed sooner		60% (compared to the project duration with No RB)	34% (compared to the project duration with 10% RB)	0% (compared to the project duration with 30% RB)

Table 4.8. Completion on time and shortening of Project 3 duration, uncertainty 0.1

On the basis of the analysed data the 50% resource buffer, obviously, would not be recommended for this project. Both 10% and 30% buffers could bring benefits to the project.

4.2.4. Summary

Three projects were analysed and described in this section. All three had the same characteristics (order strength, resource use and resource constrainedness, number of activities); all three were under the same low uncertainty of 0.1. However, all three projects showed different behaviour.

Project 1 could benefit from all sizes of resource buffers. The magnitude of the benefit and the choice of resource buffer size depend on many factors, such as: cost of additional resources or additional timing for resource buffers, the benefits of finishing a project earlier, net present value, cash flows, interests of stakeholders, importance of finishing on time, and many more.

Projects 2 and 3 could benefit from 10% or 30% resource buffers. For Project 2 and Project 3 there was no justification to insert 50% resource buffers. This size of resource buffer would bring no benefit to the project.

It might be tempting to conclude that a 50% resource buffer is too large for projects under low uncertainty. However, if it is very important that project completion occurs as early as possible, and the cost of additional resources or time for resource buffers is relatively low compared to the benefits of finishing earlier, then a 50% resource buffer could be a good decision for Project 1.

The analysis of these three projects shows that it is not possible to identify the most suitable size of resource buffer to fit all projects with the same characteristics. The projects demonstrate different results.

4.3. Medium uncertainty projects 0.3

4.3.1. Project No. 1

The box-and-whisker plot in Figure 4.7 shows much longer whiskers for Project 1 under uncertainty 0.3 than under uncertainty 0.1. Certainly, the higher uncertainty leads to more widely spread results.

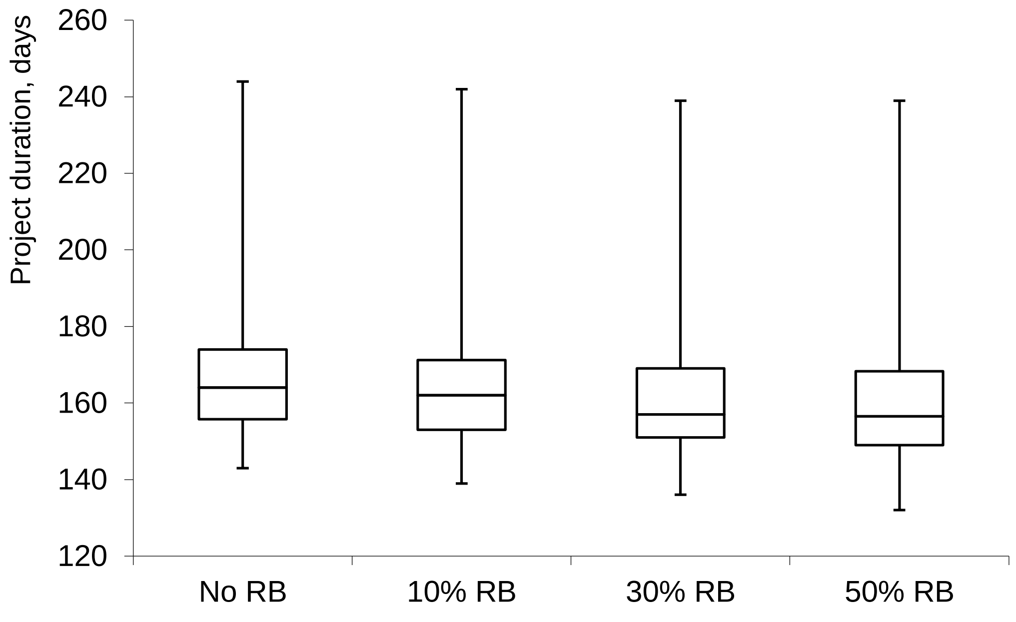

Fig. 4.7. Box-and whisker plot for Project 1, uncertainty 0.3

The changes because of the applied resource buffers in the median Project 1 duration under uncertainty 0.3 are similar to the changes that occurred when the project was under uncertainty 0.1. For the lower uncertainty the difference in median was 3 days (between no RB and 10% RB) and 2 days (between 10% RB and 30% RB), while under the average uncertainty 0.3 the difference in duration median was 2 days (between no RB and 10% RB) and 5 days (between 10% RB and 30% RB) (Tables 4.3 and 4.9).

	No RB	10% RB	30% RB	50% RB
Median	164	162	157	157
Min	143	139	136	132
Max	244	242	239	239
Q_1	156	153	151	149
Q_3	174	172	169	169

Table 4.9. Median, minimum, maximum and quartile values of Project 1 duration, uncertainty 0.3

It is important to notice that feeding buffers and project buffers did not protect the schedule from late completion. 1% of project iterations were not finished on time. But when the 30% resource buffer was applied, the situation became different and 100% of project iterations were finished ahead of deadline.

The use of the 50% resource buffer helped to shorten the project duration more often (compared with the 30% resource buffer) under uncertainty 0.3 than uncertainty 0.1: 35% of project iterations and 11% correspondingly (Tables 4.4 and 4.10).

Analysis of the results shows that Project 1 could benefit from all sizes of resource buffers, in both cases of low and average uncertainty. The 30% and 50% resource buffers in the case of average uncertainty 0.3 increase the chance of finishing ahead of deadline. It is more likely that a 50% resource buffer would shorten the project duration than it would do under low uncertainty. The bigger buffer becomes more attractive when uncertainty increases.

	No RB	10% RB	30% RB	50% RB
Project completed before deadline	99%	99%	100%	100%
Project completed sooner		68% (compared to the project duration with No RB)	55% (compared to the project duration with 10% RB)	35% (compared to the project duration with 30% RB)

Table 4.10.Completion on time and shortening of Project 1 duration, uncertainty 0.3

4.3.2. Project No. 2

When Project 2 was under low uncertainty 0.1, a 50% resource buffer was not recommended. The situation changes when the same project is under average uncertainty 0.3. Now the 50% resource buffer decreases the median project duration by 1 day, compared with the situation where the 30% resource buffer is used (Table 4.11). Also, a 10% resource buffer brings the benefit of a 3 day shorter project duration (Table 4.11), whereas this was only 1 day in the case of low uncertainty (Table 4.5).

The project was finished on time or before the deadline in all the simulation iterations. However, the insertion of 10%, 30% and 50% resource buffers helped to shorten project duration much more often under uncertainty of 0.3 (Table 4.12) compared with uncertainty of 0.1 (Table 4.6): 46%, 28%, 12% and 32%, 11%, 0%.

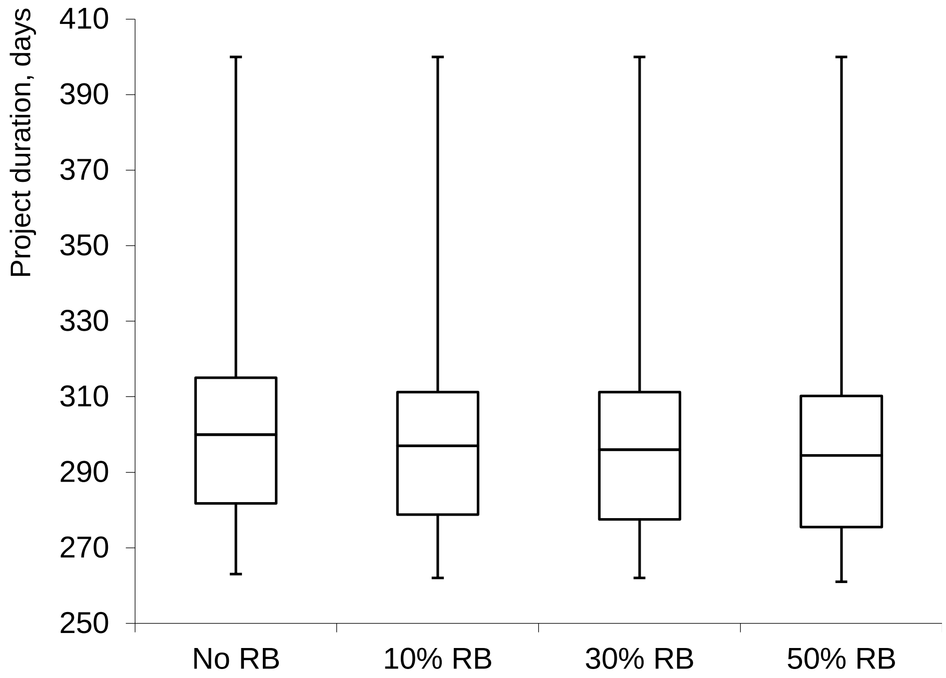

Fig. 4.8. Box-and whisker plot for Project 2, uncertainty 0.3

	No RB	10% RB	30% RB	50% RB
Median	300	297	296	295
Min	263	262	262	261
Max	400	400	400	400
Q_1	282	279	278	276
Q_3	315	311	311	310

Table 4.11. Median, minimum, maximum and quartile values of Project 2 duration, uncertainty 0.3

	No RB	10% RB	30% RB	50% RB
Project completed before deadline	100%	100%	100%	100%
Project completed sooner		46% (compared to the project duration with No RB)	28% (compared to the project duration with 10% RB)	12% (compared to the project duration with 30% RB)

Table 4.12.Completion on time and shortening of Project 2 duration, uncertainty 0.3

Project 2 confirms the conclusion made from the analysis of Project 1: larger resource buffers bring more benefits when uncertainty increases. For both projects all sizes of resource buffers could be selected, depending on the costs and other factors.

4.3.3. Project No.3

Similarly to Project 2, Project 3 demonstrated different results when uncertainty increased. Under low uncertainty, the 50% resource buffer did not cause any difference in project duration. Although the median duration value did not change under average uncertainty for Project 3, as well as for Project 2, even 36% of the projects were completed sooner when the 50% resource buffer was applied (Table 4.14).

Resource buffers had a much bigger influence on the project duration median under uncertainty 0.3 than they had under lower uncertainty. Visually, it is well represented in Figure 4.9, where the median value is seen to be decreasing with the bigger size of resource buffer.

The changes in the median were 9 days (10% resource buffer) and 16 days (30% resource buffer) under 0.5 uncertainty (Table 4.13), while it was only 6 days (10% resource buffer) and 2 days (30% resource buffer) under 0.1 uncertainty (Table 4.7).

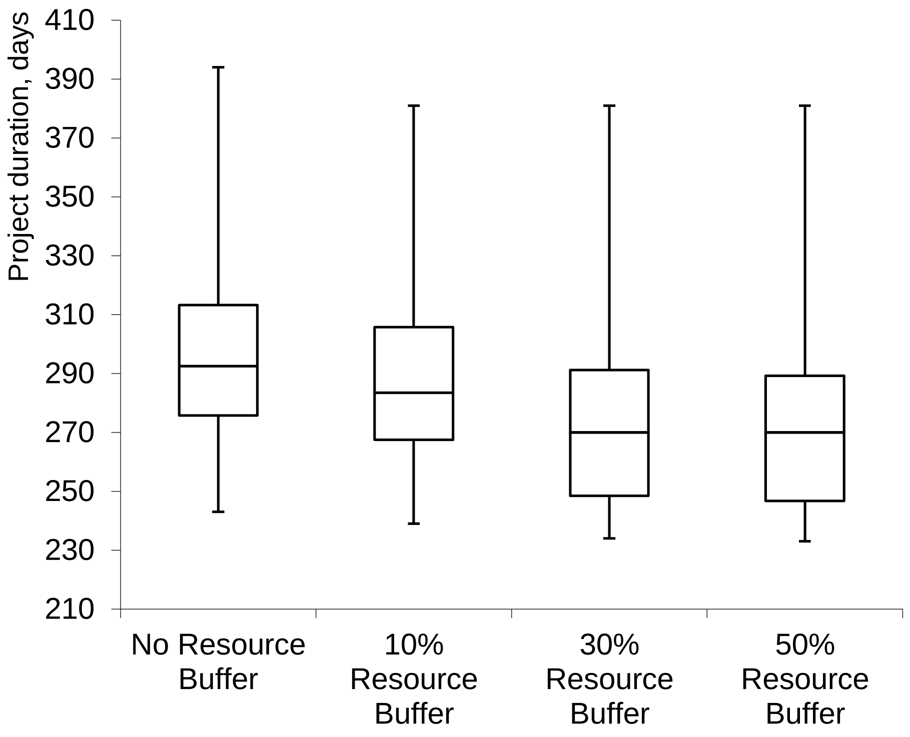

Fig. 4.9. Box-and whisker plot for Project 3, uncertainty 0.3

	No RB	10% RB	30% RB	50% RB
Median	293	284	270	270
Min	243	239	234	233
Max	394	381	381	381
Q_1	276	268	249	247
Q_3	313	306	291	289

Table 4.13. Median, minimum, maximum and quartile values of Project 3 duration, uncertainty 0.3

	No RB	10% RB	30% RB	50% RB
Project completed before deadline	100%	100%	100%	100%
Project completed sooner		82% (compared to the project duration with No RB)	66% (compared to the project duration with 10% RB)	36% (compared to the project duration with 30% RB)

Table 4.14.Completion on time and shortening of Project 3 duration, uncertainty 0.3

4.3.4. Summary

Resource buffers bring more benefits in terms of project duration when the uncertainty is higher.

The 50% resource buffer was not recommended for Project 2 and Project 3 when the uncertainty was low, but it decreased the value of the duration median for the same projects when uncertainty was average. Additionally, when resource buffers were applied, the project duration median moved to the left by a larger number of days under uncertainty 0.3 than under uncertainty 0.1. Finally, the project simulation iterations showed that resource buffers shorten project duration more often under higher uncertainty.

All sizes of resource buffers could be a good choice for all of the three projects under average uncertainty. All the projects showed different amounts of time savings, and different percentages of the shortened duration iterations. For example, if 30% resource buffer is inserted instead of a 10% resource buffer, 5 days could be saved on average for Project 1, only 1 day for Project 2 and even 16 days for Project 3. It is possible that a saving of 1 day would be considered too small to apply resource buffers (or it might not if, for example, the cost of additional time or resources is negligible), but a saving of 16 days could be considered important when deciding whether to apply resource buffers. Again, the most suitable size of resource buffer should be determined for a specific project, and with consideration of other factors.

4.4. <u>Projects under high uncertainty</u>

4.4.1. Project No. 1

The results of Project 1 under high uncertainty show interesting findings. The median value of the project duration under average uncertainty decreased by larger amounts when resource buffers were inserted compared to the low uncertainty environment. One could hope that in an environment of high uncertainty 0.5, the resource buffers would help to save time by an even larger amount. However, this is not the case for Project 1. The median value changed by 1 day when 10% resource buffer was applied, by 5 days when 30% resource buffer was applied and by 1 day when 50% resource buffer was applied (Table 4.15). To compare it with uncertainty 0.3, the results were: 2, 5 and 0 days correspondingly (Table 4.9).

The difference between the upper and lower quartiles (the interquartile range), as well as the difference between the minimum and maximum values of the project duration, increased when the uncertainty was higher (Figure 4.10). The same result could be seen when the project was compared under low and average uncertainty.

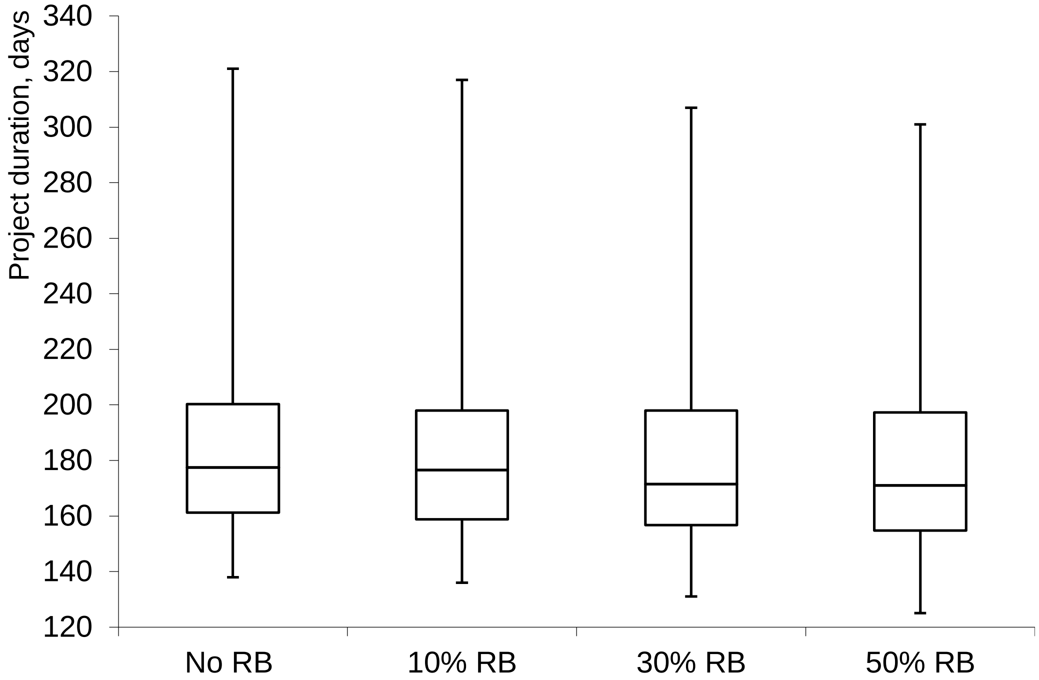

Fig. 4.10. Box-and whisker plot for Project 1, uncertainty 0.5

	No RB	10% RB	30% RB	50% RB
Median	178	177	172	171
Min	138	136	131	125
Max	321	317	307	301
Q_1	160	158	156	154
Q_3	201	198	198	198

Table 4.15. Median, minimum, maximum and quartile values of Project 1 duration, uncertainty 0.5

An important finding was that the feeding buffers and the project buffer did not protect the project duration in 6% cases. Inserting a 10% resource buffer helped to reduce the percentage of late project to 5% cases. Application of 30% resource buffers helped to decrease this number to 4% (Table 4.16).

	No RB	10% RB	30% RB	50% RB
Project completed before deadline	94%	95%	96%	96%
Project completed sooner		56% (compared to the project duration with No RB)	46% (compared to the project duration with 10% RB)	28% (compared to the project duration with 30% RB)

Table 4.16.Completion on time and shortening of Project 1 duration, uncertainty 0.5

4.4.2. Project No. 2

The changes in the value of project duration median were greater for Project 2 when it was simulated in the high uncertainty environment 0.5 than in the average uncertainty environment of 0.3. The median value changed by 3 days when the 10% resource buffer was applied, by 9 days when 30% resource buffer was applied and by 4 days when 50% resource buffer was applied (Table 4.17). To compare it with uncertainty 0.3, the results were: 3, 1 and 1 days correspondingly

(Table 4.11). These findings are not the same for Project 1, where the savings of time were very similar in both cases of 0.3 and 0.5 uncertainty (Section 4.4.1).

Certainly, when the uncertainty is high, the interquartile range increases significantly (Figure 4.11).

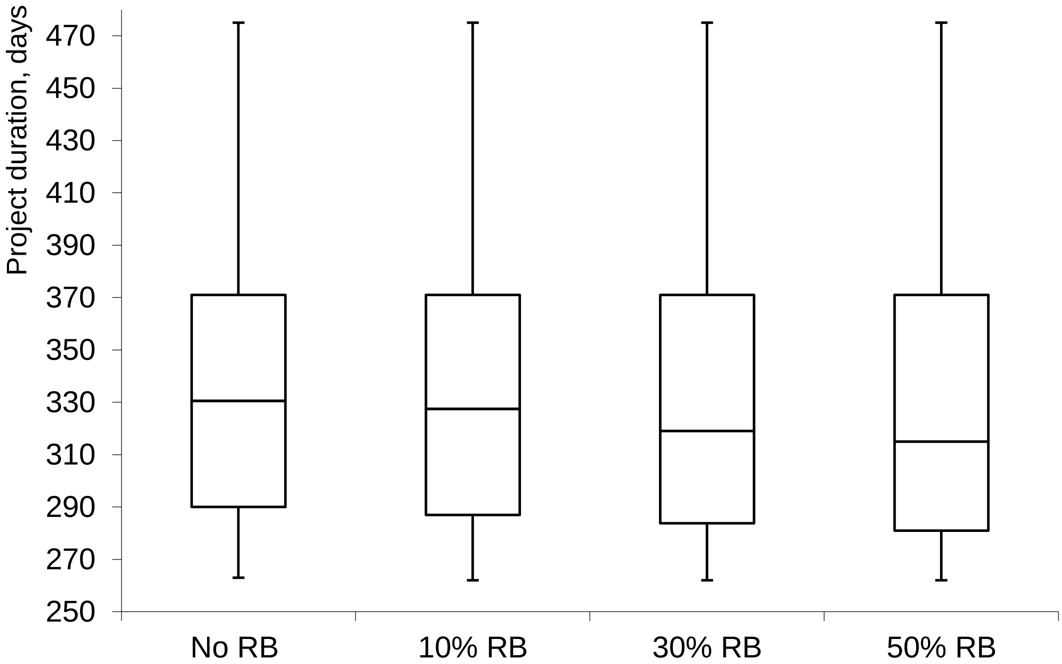

Fig. 4.11. Box-and whisker plot for Project 2, uncertainty 0.5

	No RB	10% RB	30% RB	50% RB
Median	331	328	319	315
Min	263	262	262	262
Max	475	475	475	475
Q_1	290	287	284	281
Q_3	371	371	371	371

Table 4.17. Median, minimum, maximum and quartile values of Project 2 duration, uncertainty 0.5

The percentage of project iterations that finished on time was the lowest of all investigated projects, i.e. 88%. Unfortunately, the application of 10% resource buffers helped to increase this percentage by 1%, while 30% and 50% resource buffers did not lead to any increase in the percentage of on-time project iterations (Table 4.18).

	No RB	10% RB	30% RB	50% RB
Project completed before deadline	88%	89%	89%	89%
Project completed sooner		40% (compared to the project duration with No RB)	31% (compared to the project duration with 10% RB)	20% (compared to the project duration with 30% RB)

Table 4.18.Completion on time and shortening of Project 2 duration, uncertainty 0.5

4.4.3. Project No. 3

The box-and-whisker plot in Figure 4.12 visually demonstrates that of all the analysed projects, the resource buffers have the biggest effect in terms of decreasing project duration for Project 3 (Figure 4.10 and Figure 4.11). While Project 1 had only 1 day (10% RB), 5 days (30% RB), and 1 day (50% RB) (Table 4.15), and Project 2 had 3 days (10% RB), 9 days (30% RB) and 4 days (50% RB) (Table 4.17) change in the value of project duration median, the Project 3 had even 10 days (10% RB), 17 days (30% RB) and 5 days (50% RB) change in the value of project duration median (Table 4.19).

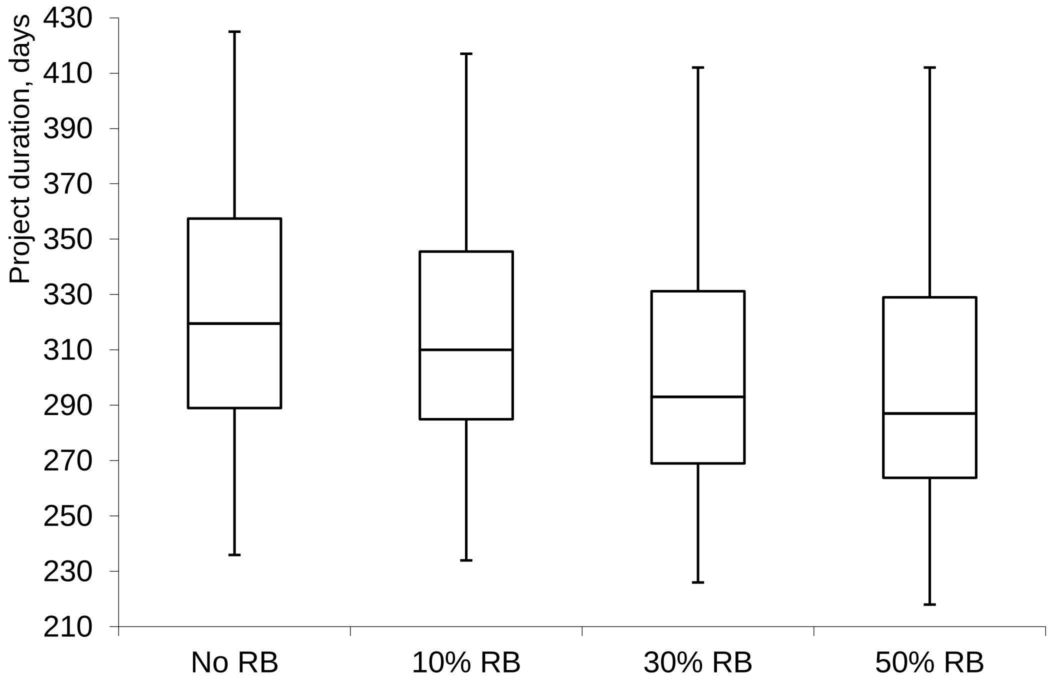

Fig. 4.12. Box-and whisker plot for Project 3, uncertainty 0.5

	No RB	10% RB	30% RB	50% RB
Median	320	310	293	287
Min	236	234	226	218
Max	425	417	412	412
Q_1	289	285	269	264
Q_3	358	346	331	329

Table 4.19. Median, minimum, maximum and quartile values of Project 3 duration, uncertainty 0.5

All project simulation iterations were completed before the deadline. Despite this, the use of 10% resource buffers shortened the duration 74% of the times (Table 4.20). The percentage of iterations when the project duration was decreased was also very high for cases where a 30% resource buffer (65% iterations) and 50% resource buffer were used (47% iterations). The high percentage of earlier finished projects makes the 50% resource buffer attractive for this particular project. Certainly, the decision maker would still have to look at the values of the lower and upper quartile, and consider the other factors influencing decision.

	No RB	10% RB	30% RB	50% RB
Project completed before deadline	100%	100%	100%	100%
Project completed sooner		74% (compared to the project duration with No RB)	65% (compared to the project duration with 10% RB)	47% (compared to the project duration with 30% RB)

Table 4.20.Completion on time and shortening of Project 3 duration, uncertainty 0.5

4.4.4. Summary

When uncertainty increases, the interquartile range of simulated project duration becomes wider, and the differences in the minimum and maximum values larger. Unfortunately, the percentage of late projects increases under high uncertainty, i.e. feeding buffers and project buffers were not able to protect the schedule from delays for Project 1 and Project 2. While Project 3 was always finished ahead of deadline, the insertion of resource buffers helped to shorten project duration most often for Project 3.

Under high uncertainty projects 1, 2 and 3 again showed different behaviour, as they did under low and average uncertainty. Project 1 had very similar savings in the median as it had under average or low uncertainty. On the other hand, Project 3 showed an obvious increase in saving of time under higher uncertainty.

All three sizes of resource buffers could be valid for all three projects. Unfortunately, it is not possible to determine one resource buffer size, which would suit all projects. Each project should be analysed individually.

CHAPTER 5. DISCUSSION

5.1. Introduction

The main research findings are discussed in this chapter. The question of resource buffer size is analysed, and an explanation of why simulation has to be performed for every specific project is given. The solution to the problem of resource conflicts is illustrated. This is followed by a discussion of the financial aspects of resource buffer application in Chapter 5.3-5.4. The recommendations on the size of resource buffer are formulated. Finally, the validation of this research is addressed.

5.2. Research findings

The implementation of three projects with the same network characteristics (order strength, resource use and constrainedness, number of activities), but different sizes of resource buffers, and under different levels of uncertainty was simulated. The resource buffers analysed were 10%, 30% and 50% of the time resource is planned to work without interruptions before starting the work on a critical protectable activity.

Initially, it was planned to change the number of activities and the parameters of network order strength, resource use and constrainedness in order to compare the results of different projects. In this way the influence of network characteristics on the optimum size of a resource buffer could be evaluated.

However, the obtained results showed that even projects with the same network parameters behave differently, i.e. a different size of resource buffer is preferable for different projects. Therefore, there was no reason to create and analyse networks with different parameters, as this would only lead to the same research results.

The research demonstrated that the resource buffers help to reduce the overall project duration.

Other important findings were obtained:

1. It is not possible to determine one size of resource buffer that would suit all projects under different levels of uncertainties. Resource buffers should depend on the level of uncertainty and on a particular project network. Even when dealing with the same project, a smaller resource buffer might be appropriate when uncertainty is low, but when uncertainty is high a larger resource buffer might bring more benefits.
2. It is not possible to determine one size of resource buffer to suit all projects under the same level of uncertainty. Even when uncertainty is the same, resource buffers act differently among projects. While a 30% resource buffer might be a good choice for one project under high uncertainty, the same size of resource buffer might be completely useless for another project under the same high uncertainty.
3. It is not possible to determine one size of resource buffer to suit similar projects with the same network characteristics. Even when having the same values of order strength, resource use and resource constrainedness, the same network order strength and number of

activities, and the same uncertainty levels, project schedules still showed different behaviour in terms of the most beneficial size of resource buffer. Projects with the same network characteristics benefited from different sizes of resource buffers under both different and under the same levels of uncertainty.

4. The position of activities, and the way the activities are linked among each other in the network diagram, determines the magnitude of the shortened duration due to the insertion of resource buffer. This finding is explained in more detail below.
5. To determine the size of the resource buffer, the simulation of a specific project should be performed. The developed algorithm for the simulation is presented in Chapter 3.5. Using a rule of thumb to apply a 10%, 30% or 50% resource buffer to all projects does not work.

To illustrate the fourth research finding, an example has been given. Figure 5.1 shows a network with 50% resource buffers. The position of non-critical activity 9 in this network influences the fact that under low uncertainty, 50% resource buffers did not decrease the overall project duration even once, compared to the situation where 30% resource buffers were applied. Large 50% resource buffers were applied, thus enabling the finish of critical activities 7 and 8 earlier than planned. However, under low uncertainty the duration of activity 9 changes only slightly. The activity 9 then becomes the critical one and determines the overall project duration.

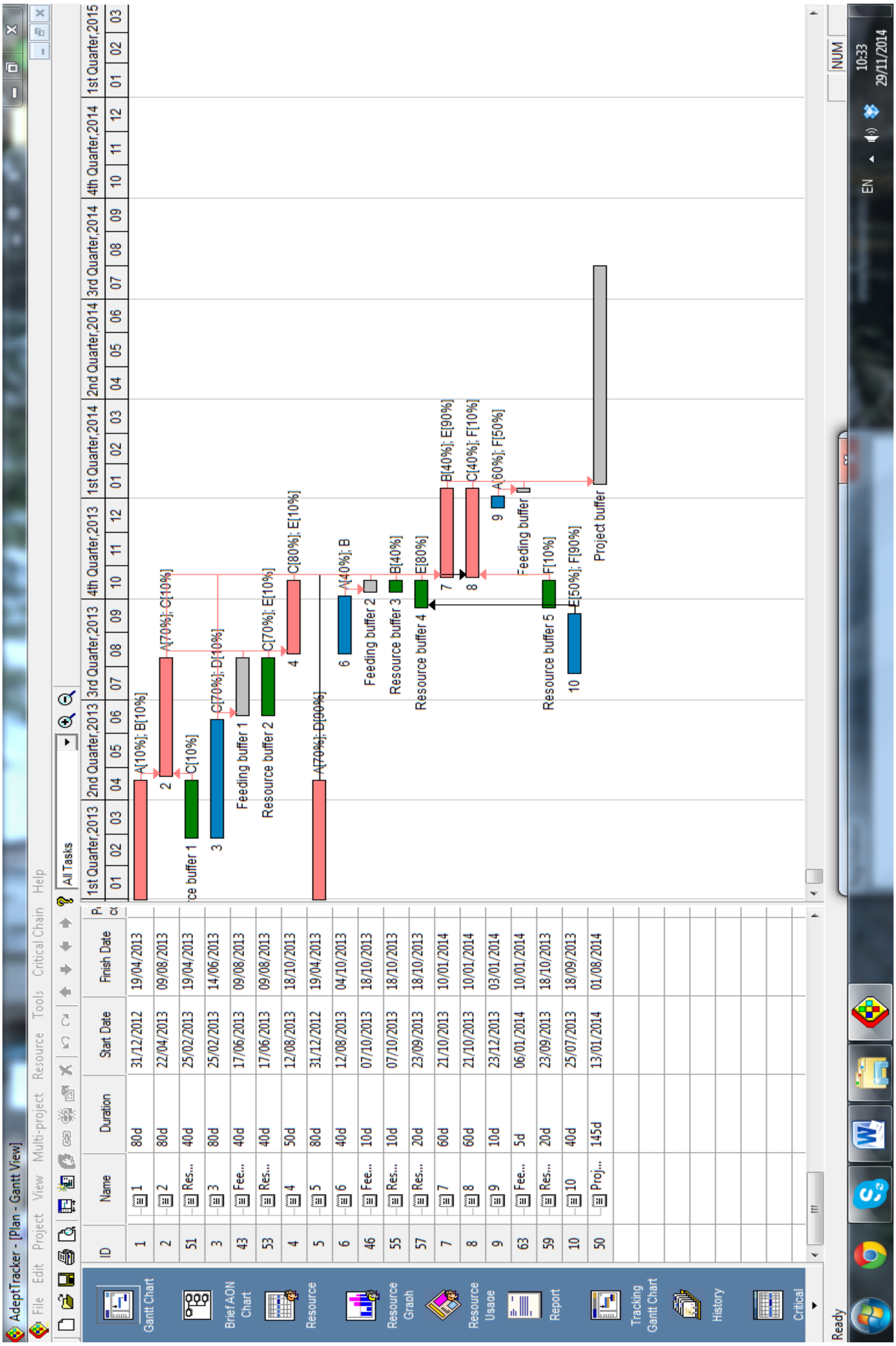

Fig. 5.1. Illustrative example of a project with 50% resource buffers

This is an illustrative example how the position of activities together with the interdependencies of activities influences the effect of resource buffers on the overall project duration.

An important finding to discuss is the resource conflicts, which occurred due to the inserted resource buffers. The same Figure 5.1 is useful for the analysis of this question. The Resource buffer No. 3 for resource B on the critical activity 7 should be 20 days (in case of 50%RB). However, it would then move activity 5 backwards by 20 days. This would create a resource conflict between activities 2 and 6 for resource A. One option to solve the resource conflict would be to move activities, using resource A, backwards. However, this would prolong the total project duration and would create gaps in the critical chain. Therefore to solve the resource conflicts, resource buffer No. 3 is allocated 10 days instead of 20, which is the largest amount of days that does not create resource conflict. The same logic applied to other resource conflicts which occurred during the research.

A significant thing to discuss is that the following information should be analysed when choosing the size of resource buffer: the median value of the simulated project duration, the minimum and maximum values of the simulated project duration, the interquartile range, the percentage of projects completed on time and the percentage of projects completed sooner because of the resource buffer applied. This recorded information section does not replace decision making, and does not give the exact solution to the problem of determining the resource buffer size. Nevertheless, it supports decision making by providing information on how much time could be saved, and the likeliness of saving it.

5.3. Financial aspects of resource buffer

The simulation results in Chapter 4 show that resource buffers help to reduce the overall project duration by different amounts of time. It also demonstrates that there might be cases where the insertion of resource buffers does not save any time in the project duration. In the latter case, obviously, there is no reason to apply any buffer at all, as resource buffers cost money (for example, equipment hired per day or wages for idle employees) or they require expenditures earlier than necessary (for example, money paid for materials ordered earlier than needed).

The most important aim of a project is to make a profit for the organisation. Therefore, as little as possible should be spent on resource buffers, i.e. resource buffers should be as small as possible. On the other hand, a 1 day delay in a project end date might cost the company much more than the cost of a resource buffer. The contrary situation is also possible, when resource buffers cost huge amounts and the penalties for late finishes or opportunity costs are negligible.

Therefore, there is no single solution to determining the size of resource buffer. The resource buffer costs should be compared to the monetary benefits of an early finish, penalties for a late finish and the opportunity costs. Based on this comparison, the decision on the exact size of resource buffer should be made.

An illustrative example is presented in the next Chapter 5.4.

5.4. Illustrative example of resource buffer use

This is a very simple example, illustrating the importance of financial issues and demonstrating the decision on the exact choice of resource buffer size.

Two projects are analysed, both having a duration of 268 days. The simulation shows that the application of a 10% resource buffer could reduce the overall project duration by 12 days, and the 30% resource buffer could save 15 days for both projects. Knowing this information, it is tempting to select the 30% resource buffer, as it saves more time.

However, it is assumed that the 10% resource buffer would cost 1000 monetary units for both Project 1 and Project 2. The 30% resource buffer would cost 3000 monetary units again for both of the projects.

The penalty for a late finish, or the award for an early finish for Project 1 is 100 monetary units per day. Is it worth applying a 10% resource buffer? The comparison is between the resource buffers cost of 1000 and penalty/award cost of 12*100=1200 monetary units, as a result of the reduced project duration. As the penalty/award is higher than the resource buffer cost, and all other factors are the same, the 10% resource buffer is recommended for this schedule. To check if the 30% buffer would be useful, the same comparison has been made. Now the numbers under comparison are 3000 and a penalty/award cost of 15*100=1500 monetary units. This means the 30% resource buffer would not be recommended.

Although, Project 2 has the same project duration, the same possibilities to save time with the help of resource buffers, and the same costs of resource buffers, the penalty/award cost is different: 2000 monetary units per day. In this case, when

10% resource buffer is applied, the comparison is made between 1000 and 12*2000= 24 000 monetary units, and when 30% resource buffer is applied the comparison is made between 3000 and 15*2000=30 000 monetary units. Of course, in both cases the resource cost is very small when compared to the costs if a project is delayed or if an early finish is awarded. For this project, even larger buffers should be simulated and possibilities to reduce duration more should be investigated.

The example illustrates how very simple financial analysis can be used when the decision on the size of resource buffer is made.

5.5. Recommendations about resource buffer

There is no simple way to decide how big the resource buffer should be. If a 30% resource buffer is found by simulation to be suitable for one project, it does not mean that it will work well for another project. The size of resource buffer cannot be determined solely considering the project duration. Is the reduction of the project duration by 10 days enough? Or is it better to increase the resource buffer and reduce the project duration on average by 12 days? In terms of time, obviously, the shortening of the project duration by 12 days would be a better choice. But if the cost of resources is a lot, and the saved 2 days do not generate a larger income, is it worth it?

The recommendation is to apply the designed simulation method, which acts as a supportive tool when making a decision. Following the simulation algorithm a scheduler/manager could receive the information about the possible savings of time, and the likeliness of savings. In combination with the financial analysis of resource buffer costs and the monetary benefits of finishing on time or ahead of schedule, the decision on the precise buffer size could be made.

5.6. Validation of results

Validation is the process of checking whether the built model correctly represents the real life system. Unfortunately, only a few publications on CCPM research address the issues of validation in practice. In most cases the authors provide artificial examples. They create an example themselves or they take an example from so called ‘project libraries’ (Project Scheduling Problem Library, Patterson tests, see Chapter 3.3.5) or they generate examples with the help of special software (ProGen, RanGen). A few of them use a real life case study (Rabbani et al. 2007; Bevilacqua et al. 2009) or three real life case studies (Ma et al. 2014). However, even if a real case is used, only the input data from the real situation is applied, but the outcomes are not tested for the real life situation. Very often simulation is applied in CCPM research, where validation is not addressed at all (for example, Xie et al. 2010).

The input data to the model in this research was not one of the real life cases. The project schedules were generated by the RanGen generator. However, the project networks and activity durations do not necessarily need to be validated. Even if an exact project schedule does not exist in practice, it does not mean that it could not be true or right in real world project management. Any schedule with any number of activities, any activity durations, and any relationships is valid. Therefore face validating (asking opinion of experts in the field) was not necessary for the input data.

There is no agreement among scientists on the probability distribution to be used for activity durations. For this research, an assumption of lognormal distribution for the simulation of activity durations was made based on the experience of other researchers (Demeulemeester and Herroelen 2002; Tukel et al. 2006). The fitting of generated random numbers to the assumed probability distributions was validated by applying Kolmogorov-Smirnov, Anderson-Darling and Chi-squared tests (Chapter 3.3.7.2). The same tests were used to validate the assumed probability of simulation results (Chapter 4.1.1). The statistical significance or difference between the results of different projects under different uncertainties and different sizes of resource buffers was checked with the Kruskal-Wallis test and the Wilcoxon Signed Rank test (Chapter 4.1.4).

The validity of simulation results increases with a higher number of simulation runs. Table 5.1. demonstrates a combination of all the project variants, for which the simulation was performed in this thesis. For every project, 100 simulation runs were done. This makes the total of 1200 simulations

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Scenario 1	Uncertainty 0.1	
	Uncertainty 0.3	
	Uncertainty 0.5	
Scenario 2	Uncertainty 0.1	Buffer size 10%
	Uncertainty 0.1	Buffer size 30%
	Uncertainty 0.1	Buffer size 50%
	Uncertainty 0.3	Buffer size 10%
	Uncertainty 0.3	Buffer size 30%
	Uncertainty 0.3	Buffer size 50%
	Uncertainty 0.5	Buffer size 10%
	Uncertainty 0.5	Buffer size 30%
	Uncertainty 0.5	Buffer size 50%

Table 5.1. Combination of all project variants

Unfortunately, it was not possible to validate the research results in a real world environment. It was known, that Balfour Beatty, Denne Construction, Day &Zimmerman, Harris Corporation, Habitat for Humanity, and Shea Homes used CCPM in their practice. They were contacted and asked if they would agree to participate in the research, and if a representative from a company would agree to discuss the research results in an interview. Unfortunately, none of the answers were positive. Shea Homes stated that they no longer use scheduling based on CCPM. Harris Corporation indicated to the splitting of divisions in their company and sold production lines, which in turn complicated the search for a company applying CCPM. The number of companies known to apply CCPM is very limited and even those who apply CCPM are reluctant to discuss the research findings.

Another option to validate the simulation results would be to apply the developed simulation algorithm to a real case, and to study if the results were the same or similar to in the research. Unfortunately, this so called ‘validating input-output transformation’ was not feasible, as it was impossible to find a real project that applied CCPM, and would also agree to share the schedule of at least one project for a case study.

Nevertheless, as the model assumptions and input data are valid, the results are valid as well. It is also important to mention that the outcome of the research is not a specific size of resource buffer, but a recommendation to follow the developed simulation algorithm for each project, in order to determine the most appropriate size of resource buffer.

CHAPTER 6. CONCLUSIONS, CONTRIBUTIONS AND FUTURE WORK

6.1. Introduction

This final chapter of the thesis starts with a review of the research objectives. The objectives presented at the beginning of the thesis will now be compared with the achievements. The research questions are briefly answered. The reader is reminded of the research hypotheses, and conclusions are made about whether the hypothesis is true, or whether it should be rejected. Next, the research limitations are addressed, followed by a discussion of the research contribution to the field of knowledge and to practitioners. Recommendations for further research are suggested in the last Chapter 6.6.

6.2. Review of objectives and achievements

This research study aimed to analyse the question of resource buffers in Critical Chain Project Management and to provide a systematic method for the use of resource buffers in Critical Chain Project Management. In order to achieve the aim, four objectives were identified:

1. *Review previous research on Critical Chain Project Management and the use of resource buffer in particular.*

The objective was reached in full.

The shortcomings of traditional project management planning techniques were identified. Two main techniques, Critical Path Method (CPM) and Programme Evaluation and Review Technique (PERT), were analysed. The drawbacks of these techniques include the neglect of human behaviour, the lack of procedures for managing multi-projects, the lost focus due to frequently changing critical path, difficult monitoring. In addition, CPM was criticised for the deterministic planning. Critical Chain Project Management (CCPM) technique overcomes the shortcomings of CPM and PERT by addressing human behaviour (trying to avoid Student's syndrome, Parkinson's Law, multitasking, overestimation in activity durations), by focusing on more stable critical chain instead of critical path, and by simplifying project monitoring with the help of fever charts. CCPM considers not only precedence relationships, but also resource availability from the very start of schedule development.

However, CCPM is still not perfect. Researchers address the questions of risk integration into CCPM, identification of critical chain, rescheduling, sizing of project and feeding buffers, determination of activity duration, communication problems with stakeholders. There are a number of suggestions trying to answer these questions and solve the problems. The further development of the suggestions and their comparison would be useful.

The literature review on CCPM also revealed the research gap, which was chosen for the research in this thesis. The question of resource buffers is ignored by both the researchers and the practitioners. The literature review revealed that researchers investigate the question of resource buffers and practitioners use resource buffers, but this is done not in the field of CCPM. However, the activities are scheduled as late as possible in CCPM and the roadrunner behaviour enables earlier starts than planned. Therefore resource buffers are even more important in schedules managed by CCPM than by traditional project planning techniques.

2. *Develop a simulation method to test the usefulness of resource buffers in CCPM projects under different uncertainty levels.*

The objective was reached in full.

The simulation method was developed for the purposes of this research, and for general use. The suggestion was made to position a resource buffer before the critical chain activity when it was performed by the resource, which was not working on the previous critical chain activity. The main performance measure of the developed simulation method was the project duration. Simulations were performed for 3 different projects under different uncertainty levels, and having different sizes of resource buffers. Random numbers were generated to simulate project execution. The simulation results demonstrated that resource buffers are useful in CCPM projects.

3. *Examine the issue of resource buffer cost.*

The objective was reached in full.

An explanation of financial issues relating to the cost of resource buffer and cost of a late finish of a project was discussed using an illustrative example.

There is no simple answer to the question whether it is worth using resource buffers in CCPM projects in terms of profit. The comparison of a resource buffer cost with the benefits from early or on time finish of a project has to be made for each specific project.

4. *Determine the optimal size of resource buffer for all projects.*

The objective was partially reached.

The simulation results showed that no optimal size of resource buffers valid for different projects could be found. Instead, the developed simulation algorithm should be applied to each specific project.

6.3. Conclusions

At the very start of the simulation method development (Chapter 3.3.2), three hypotheses were identified:

Hypothesis 1. Application of the resource buffers on average shortens project duration.

Hypothesis 2. The higher the uncertainty of the project environment, the larger the resource buffer should be.

Hypothesis 3. There is an optimum size of resource buffer, expressed in percentage of the time resource is planned to work without interruptions before starting the work on a critical chain, common across all projects.

The research confirmed the Hypothesis No. 1 should be accepted. The simulation results demonstrated that projects with resource buffers have, on average, shorter durations. They are finished on time more often, compared to the projects without resource buffers.

The research demonstrated that Hypothesis No. 2 should be rejected. Although intuitively it seems that projects in the higher uncertainty environments should be protected by larger buffers, this is actually incorrect. The simulation results demonstrated that the usefulness and size of a resource buffer depends more on the specific network, and the way that the activities link to each other, than any other factor.

The research showed that Hypothesis No. 3 should be rejected. It is not possible to find an optimal size of resource buffer that would be valid for different projects. Instead, the proposed simulation method should be applied, the suggested algorithm should be followed, and a specific project should be analysed to decide on the most appropriate size of resource buffer.

6.4. Limitations

Quantitative simulation based research is based on the assumption that models imitating the real life of operations can be created. Models are "an abstraction from reality in the sense that not the complete reality is included" (Bertrand and Fransoo, 2002). This results in knowledge about the behaviour of dependent components depending on the independent variables. The limitation of applying this kind of model is that human factors affecting operations are not considered. Simulations in this research were performed without any corrective actions to the schedule during project implementation. When executing the project, other decisions could be made: employ more workers, change the type of equipment so it is more efficient, change the supplier of needed materials, etc. These corrective actions could change the way a schedule performs.

The research presented in the thesis is limited to the case of independent activities in a schedule. Therefore, if two or more activities are affected simultaneously by the same event, the proposed simulation method might not be valid.

One more limitation relates to the assumption of unsplittable activities. In cases where activities could be split, the results of simulation could be different.

Scheduling was performed on Agile CC, with the scheduling problem solving mechanism encoded in the software programme.

6.5. Contribution to knowledge

The thesis contributes to the field of knowledge by:

1. Revealing that the problem of resource buffer use in Critical Chain Project Management is neglected.
2. Designing the simulation method for resource buffer allocation and sizing.
3. Demonstrating that resource buffers are beneficial and should be used in Critical Chain Project Management.

These three main contributions are discussed in more details below.

This thesis contributes to the field of knowledge first of all by attracting attention to the neglected problem of resource buffer. As no publications were found which related to resource buffers in Critical Chain Project Management, and there has been a tendency in recent publications not to mention resource buffers at all, there is a danger that schedules will not be protected from the resource unavailability, resulting in late and over-budget projects. This revealed gap in research is important not only to the researchers' community, but also to the practitioners and CCPM software developers.

Next, simulation method for buffer sizing was developed, explained and tested. This method is applicable to any project. It is not a decision making tool, but supports the decision making with the necessary information on how much time could be saved if a different size of resource buffer is applied.

Finally, the research presented in the thesis demonstrated that resource buffers are beneficial, and should be used in Critical Chain Project Management. The size of the resource buffer should be determined for each project, depending on the results of the developed simulation method and the financial analysis.

These findings could be of interest to practitioners using CCPM to manage their projects. The practitioners could apply the developed simulation algorithm to real world schedules, in this way finishing projects earlier and increasing profits.

The research findings could also be of interest to researchers trying to improve Critical Chain Project Management. This research attracts attention to the neglected questions surrounding resource buffers, demonstrates the benefits of using resource buffers, and raises further questions on resource buffer sizing. The further questions are discussed in the following chapter 6.6.

6.6. Future research

There are a few proposals for the further research on resource buffers. One of them would be to introduce reactive policies into the developed simulation method. During project execution, if one resource buffer is used up, it would be possible to review the schedule and update other resource buffers. Also by monitoring buffer consumption, corrective actions could be simulated: for example more resources employed or other suppliers of resource found.

Another suggestion would be to analyse and simulate different sizes of resource buffers for different activities, depending on the level of uncertainty for a specific activity, rather than for the whole project.

Finally, an important area for future research would be to analyse the use of resource buffers outside the restrictions of a single project environment, by extending it to a multi-project case.

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APPENDICES

Appendix A. Article on Critical Chain Project Management

Critical Chain Project Management: Theory and Practice

Abstract

Critical chain project management (CCPM) promises significant advantages in the field of project planning. This review paper summarizes the theoretical problems identified in the academic literature, and emphasizes the issues which need to be addressed by CCPM. The theoretical analysis is then compared to the status of CCPM in practice by examining the available CCPM software products. The study investigates the gap between theory and practice: between researchers' recommendations, and what is currently implemented by software developers. The paper recommends ways to close the gap between theory and practice and to enable project managers to achieve the promised benefits of implementing CCPM.

Keywords: critical chain; managing time; project scheduling; software.

1. Introduction

Scheduling attracts substantial attention from project management researchers and practitioners. Schedules serve as the basis for planning activities in time, allocating required resources in an optimum way, ordering external, and allocating internal resources. They are also the basis for forecasting cash flow, monitoring project performance, and taking corrective actions. They determine the commitments to customers and form the basis of agreements with subcontractors, creating a system of accountability. Literature on project delay (Assaf and Al-Hejji, 2006) and project success factors (Divakar and Subramanian, 2009) emphasize the importance of accurate scheduling.

Critical Chain Project Management (CCPM) is a project scheduling technique that enables the sequencing of activities based on precedence relationships, taking into account resource availability. It focuses on critical activities and resources, while simplifying project monitoring. Using CCPM, activity durations are reduced, and a margin of safety is included at the end of a project as a project buffer. By using reduced activity durations, CCPM takes into account typical human behaviour, such as overestimation of activity duration. It also avoids problems such as Student syndrome (postponing the performance of an activity until the last minute) and Parkinson's law (work expanding to fill the time available (Parkinson and Osborn, 1957)). It is argued that CCPM takes advantage of early activity finishes, shortens project duration, and increases the stability of a schedule.

The significance of CCPM in theory and in practice can be seen from a number of published books (Goldratt, 1997, Leach, 2004, Leach 2005, Newbold, 1998, Woeppel, 2006), and from intensely used discussion groups (www.prochain.com/discussion.html, yahoo and linked-in discussion groups, etc.). To support the method, a number of software packages have been developed (see Section 3).

Since its development, CCPM has received significant attention from researchers, beginning with descriptions of the technique (Rand, 2000, Steyn, 2001), debates over innovation (Hejducki and Rogalska, 2004, Trietsch, 2005a) and comparison with the Critical Path Method (Lechler, 2005). Also, literature highlights the advantages and cases of successful implementation in practice (Robinson and

Richards, 2010, Newbold, 1998, Leach, 1999), while the advantages of CCPM are questioned due to the lack of scientific validation of the assumptions and methods proposed by E. Goldratt, the developer of CCPM (Herroelen and Leus, 2001, Herroelen et al., 2002, Pinto, 1999, Raz et al., 2003, Trietsch, 2005a). More recent research considers improving CCPM, and suggests different algorithms and methods to overcome its shortcomings (see Section 4).

The aim of this paper is to review the literature on CCPM in the single project environment, compare CCPM theory and practice, uncover the gap between research and software implementation, and propose possible directions for future research.

In the next section, we provide a brief description of CCPM. Section 3 presents methods used for revealing the state of CCPM theory and practice. Section 4 includes the results of the literature review and comparison with CCPM practice. The important issues of human behaviour are described in Section 5. The paper ends with conclusions and recommendations for future research.

2. Fundamentals of Critical Chain Project Management

This section provides a brief description of CCPM as defined by Goldratt (1997) and Newbold (1998). Unlike other scheduling techniques, such as Critical Path Method (CPM) or Programme Evaluation and Review Technique (PERT), it resolves resource constraints in the first step of scheduling. The longest path, determined by activity interdependencies and resource availability, is called the critical chain. An underlying assumption of CCPM is that traditionally, activity duration times are overestimated and contain “safety time” to ensure they can be completed on time. Use of CCPM involves removal of safety times from the duration of individual activities. Instead, the safety time is aggregated in strategically placed time buffers, thus shortening the total project duration. CCPM uses three types of buffers: project, feeding and resource buffers. The project buffer is placed at the end of a project to protect the due date. Feeding buffers protect critical chain activities from delays in non-critical activities, and are placed at the points where non-critical chains join the critical chain. Resource buffers are used to protect the critical chain from resource unavailability and are placed at the points where a new resource is starting work on a critical activity.

Goldratt (1997) suggests that the activity duration used for CCPM should be set at 50% of the estimated duration. The remaining half of the duration should be used for the project buffer. This is the so called Cut and Paste method (C&PM), based on the statistical law which states that "standard deviation of the sum of a number of mutually independent random variables is less than the sum of the individual standard deviations" (Raz et al., 2003). The underlying assumption is that about one half of the activities in a project will finish on time or beforehand, while the other half will not meet their deadline. It is argued that application of this sizing approach leads to approximately 25% shorter project durations compared to resource levelled critical path schedules (Robinson and Richards, 2010).

Another method for buffer sizing is the root square error method (RSEM), which applies two estimates for each task: the safe estimate of 90% probability and the shortened estimation of 50%. The size of buffer is then the square root of the sum of squares between the safe estimate, and the shortened duration for each activity in the chain leading to the buffer (Newbold, 1998). Its advantage is that it does not create extreme cases – very large or very small buffers (Tukel et al., 2006).

Moreover, CCPM applies a different monitoring mechanism. Instead of concentrating on a frequently changing critical path, CCPM uses fever charts which divide a project buffer into three areas, marked by different colours: green, yellow and red. The risk of not completing a chain of activities is measured by the amount of buffer consumption (Steyn, 2001). Preventive actions can be taken according to the size and trend of buffer consumption.

3. Research methods

This section describes the methods used to identify the state of CCPM theory and practice.

The state of CCPM theory was revealed by performing an extensive literature review with the aim to define the critical issues of current knowledge.

The state of CCPM practice was evaluated by analysing commercially available CCPM software packages: Agile CC, Aurora-CCPM, Being Management 3, CCPM+, Exepron, Lynx, ProChain Project Scheduling (PPS), and Sciforma 5.0. The software was evaluated by reading manuals and tutorial exercises, followed by exchange of e-mails with representatives from the companies. The CCPM software Concerto was excluded from the research due to the lack of availability of manuals or tutorials, and unwillingness of the company to participate in the research.

4. CCPM theory and practice

After reviewing the literature, the issues that related to critical sequence, the start of activities, task prioritisation, human behaviour, robustness, assumption of independent activities, uncertainty, activity duration, buffers, subcontractors and monitoring were identified as receiving the most attention by researchers. These parameters were then analysed during the software study, examining the usage of suggested CCPM improvements by researchers and looking for new unpublished methods applied in software.

4.1. Critical sequence

Critical sequence in CCPM is the longest path, determined by resource and task precedence dependencies. Where more than one critical sequence exists, Goldratt’s proposal is to choose one as the critical chain (Goldratt, 1997). This solution has been criticised (Herroelen et al., 2002), arguing that the choice of critical chain has to be made more carefully, as it leads to different baseline schedules and different project durations. Researchers have suggested domination rules and criticality probability for the determination of the most critical chain (Rabbani et al., 2007).

However, most of the software products apply only task precedence and resource constraints for determining the critical chain. Only Aurora-CCPM allows preference constraints to be used instead of precedence constraints. When more than one critical chain exists, the software usually chooses the first critical chain appearing on a network (Being Management 3, Lynx). Other software applications offer more advanced ways to choose the critical chain: for example, a scheduler can list the tasks which should be on the critical chain by ID order (CCPM+). PPS takes into account activities from all critical chains by allowing multiple endpoints, each of which may have a defined relative priority and their own buffer. In standard mode it also allows multiple parallel critical sequences to be included in the critical chain. Aurora-CCPM offers a feature, where some tasks can be biased to be on the critical chain. Moreover, the critical chain can be selected by a proprietary algorithm according to predefined rules: random, most stable or least stable.

The analysis shows that although little attention is paid by researchers to the problem of determining the critical sequence, some software developers offer different solutions.

4.2. Start of activities

CCPM differs from CPM by arranging activities 'as-late-as-possible' (ALAP) with feeding buffers to protect the critical chain. It is argued that this decreases the time lost by changes in scope and specifications, and postpones the need for cash. However, the allocation of tasks 'as-late-as possible' can have a crucial disadvantage as buffers might fail to protect the project finish date. Moreover, some tasks (for example, activities with incoming cash flow) could be better arranged following an 'as-soon-as-possible' (ASAP) rule. Therefore guidelines could be published to help project managers or estimators decide on the appropriate rule to start a specific activity.

Software products allow the user to select either the ALAP or ASAP rule (Being Management 3, Aurora-CCPM, Lynx, PPS, Sciforma 5.0). However, there are no recommendations on when to use the ASAP rule. Exepron and Sciforma 5.0 allow using ALAP for planning purposes and ASAP during execution (Exepron, Sciforma 5.0).

4.3. Task prioritisation

While CPM/PERT gives higher priority to tasks on the critical path, CCPM allocates higher priority to tasks on the critical chain having the largest penetration into the buffer. However, strategically important projects, or those associated with high delay penalties, might be more important than buffer penetration ratio (Raz et al., 2003). Moreover, Trietsch (2005a) notices that once a system allocates 100% of criticality to a single bottleneck, the marginal waste of non-bottleneck resources approaches 100%. Therefore the criticality should be related to marginal resource costs. It might be not worth keeping the critical resource 100% busy, while other resources have extra capacity and are idle.

The suggestions made by researchers to date are to prioritise activities by multiplication of average time, criticality index and cruciality index, and to form an optimal subset of them (Rabbani et al., 2007). Another suggestion for determining the priority of tasks is related to calculation of risk as a multiplication of probability and consequences (Bevilacqua et al., 2009).

Some software products apply the original rule for task prioritisation depending on the penetration of project buffer (Being Management 3, Agile CC). Sciforma 5.0 lets the user assign the task priority level from 0 to 1 billion. PPS calculates the impacts to the project buffer associated with delaying each task to help prioritise activities. Aurora-CCPM uses different ‘prioritizers’ based on a proprietary algorithm. Exepron prioritises tasks according to the remaining duration of predecessors, trying to reduce the accumulated risk of finishing the project behind the deadline.

It can be seen that some products applied in practice offer suggestions on how to prioritise tasks. However, there is still a need for the others to incorporate the existing methods for prioritisation or create new ones.

4.4. Robustness

Robustness in CCPM is related to changes in schedule during both the initial planning stage and during project execution.

During the initial planning stage, the insertion of buffers might create difficulties. The inserted feeding buffers sometimes change the critical chain. The alternative path where a feeding buffer has been added might become longer than the critical chain itself, as shifting the activities of a noncritical chain backwards may create a situation when a noncritical chain has to be started before the planned beginning date of a project. Moreover, feeding buffers may create gaps in a schedule. Next, feeding buffers might sometimes fail to protect the critical chain when delays in non-critical activities occur. Finally, the insertion of both resource and feeding buffers can create resource conflicts as activities are moved in a schedule. Solving the resource conflicts can become a total rescheduling problem.

Suggestions in recent literature on how to overcome the pitfalls of buffer insertion include the re-levelling of resources after inserting buffers (Robinson and Richards, 2010). The suggestion for closing small gaps is to reduce the feeding buffer, and to move the reduced amount to the project buffer (Leach, 2004). Another proposal to address the problem of resource conflicts caused by insertion of feeding buffers is to identify the feeding buffer insertion point (Zhao, 2010). The most cited way to overcome the problems created by feeding buffers is to eliminate feeding buffers from CCPM completely (Long and Ohsato, 2008, Lechler et al., 2005). This approach is called a simplified CCPM. However, there is still need to prove if the suggestion is valid.

Some of the suggestions, although not yet proven by researchers, have been implemented in practice. The latest version of PPS allows use of algorithms that provide feeding buffer protection without adding feeding buffers. CCPM+, Being Management 3, Lynx and traditional mode of PPS allow switching feeding buffers off, setting their value to zero. Sciforma 5.0 lets feeding buffers dissolve manually after placement. On the other hand, Aurora-CCPM, Exepron and Sciforma 5.0 still use feeding buffers. Lynx copes with gaps occurring due to the insertion of feeding buffers by having an option "Consume feeding buffers when they extend the duration of critical chain." It also has an option to insert buffers for special intermediate milestones. Aurora-CCPM and Lynx permit a re-level after the buffers are inserted. PPS traditional mode allows any gaps in the critical chain created by feeding buffers to be removed, consolidating that time into the project buffer. Representatives from Exepron claim that the scheduling algorithm does not permit critical chain change because of the inserted feeding buffer. Moreover, they state that the 1st task scheduled will always be the 1st task on the critical chain, and the inserted feeding buffer will not move the non-critical chain before the start of the project.

The second issue regarding robustness of CCPM schedules is related to robustness during project execution. This means that the robustness of a schedule can only be evaluated in conjunction with real life implementation. While the critical path often changes during project execution, the critical chain is said to be constant and rescheduling is not recommended, as buffers should protect from changes in a schedule. However, the bottleneck resource is not stable (Raz et al., 2003, Trietsch, 2005a). Moreover, there might be cases when shortening of duration is more advantageous than the robustness of a schedule. Therefore rescheduling might be recommended, taking into account transaction costs (costs of communication, coordination and negotiation). Without rescheduling, the old critical chain may no longer be the constraint. Herroelen and Leus (2004) claim, that "CCPM is not adapted for environments with very high uncertainty". Frequent rescheduling is required in high uncertainty projects as unforeseen new tasks are added.

Suggestions to make the CCPM schedules more robust include:

- Apply either local repair or global reschedule, performed by branch and bound method (Cui et al., 2010). Local repair involves a simple movement of activities which have resource or precedence conflict. Global reschedule means creating a completely new schedule;
- Build an expert system, which would reset all the due dates (Blackstone et al., 2009);
- Reschedule the project implicitly: apply heuristics, for example, management judgement, minimum slack or the earliest due date to choose the next activity (Lechler et al., 2005); and
- Reschedule project explicitly: compute optimal plan by forward pass while considering transaction costs ((Lechler et al., 2005).

The software applications suggest continuously re-evaluating the critical chain (Lynx), deriving new task priorities from the updated buffer incursion information (Aurora-CCPM, PPS), and re-running planning algorithms when major planning has to be re-done (PPS, Sciforma 5.0). In traditional mode of PPS, priorities are updated, but the tasks on the critical chain do not change.

Further research would be useful to find the best method for rescheduling. This could include adding different types of disruption in the analysis of rescheduling, adding a tabu search, applying simulated annealing, or genetic algorithm in local and global reschedule (Cui et al., 2010). Effective and efficient solution algorithms and quality robust baseline schedules are still needed. This could include minimizing the number of rescheduled activities or the number of times the activity is rescheduled (Herroelen and Leus, 2004). Sensitivity analysis could be applied for rescheduling. The question posed by Herroelen and Leus (2004), which sensitivity analysis could answer, is: “What are the limits to the change of a parameter such that the solution remains optimal?”

4.5. Assumption of independent activities

CCPM assumes that activities are independent. However, in real life the same factors might sometimes have an effect on different activities (for example, weather disruptions can influence several construction tasks at the same time). Therefore, the durations of activities will tend to change jointly, and the duration of the critical chain, and therefore the project, will be affected (Long and Ohsato, 2008). As a result, the principle of aggregation of safety times into the project buffer and the central limit theorem might not be valid for CCPM, and the assumptions of statistical independence, on which both the cut and paste method (C&PM) and root-square-error-method (RSEM) buffer sizing methods are based, are questionable. Furthermore, if activities are independent, they can still be subject to the same systematic errors and bias (Trietsch, 2005b). The central limit theorem is not valid for a path with less than four tasks (Moder and Phillips, 1970). How should the feeding buffers be sized when less than four tasks make up the feeding chain? How should the buffers be sized when activities are dependent?

These questions are not considered in CCPM software applications and could lead to significant disadvantages in practice. Only CCPM+ gives the advice to combine tasks into longer chains, so as not to have a chain of less than four tasks. However, this is mentioned in tutorials only and might be missed by a practitioner.

4.6. Uncertainty

CCPM tries to manage uncertainty by applying buffers. However, initial suggestions to size the buffers using the cut and paste method (C&PM) or root-square-error method (RSEM) might create buffers that fail to protect from uncertainty, and so CCPM should be combined with risk analysis and mitigation tools.

A number of researchers have already tried to incorporate risk elements into buffer sizing methods. For example, new buffer sizing methods have been developed which use three time estimates as in PERT (Liu et al., 2009, Li et al., 2010). Liu et al. (2009) suggest incorporating the effect of an activity position in a project, as the further the activity is from the start of a project, the greater uncertainty it has. Li et al. (2010) suggest using the parameter of the degree of risk in the formula for calculating the project buffer size. However, there is no detailed explanation on how to quantitatively evaluate the degree of risk. Leach (2004) presents the Bias Plus SSQ method. Together with the buffer calculated by the RSEM method (RSEM is also called SSQ), a fixed portion of buffers is added. The fixed part considers variation and bias. Shu-Shun and Shih (2009) state, that the project buffer should include both the risk and the effect of duration extension. Bevilacqua et al. (2009) developed a method where the priority of activities is defined by a priority index, which is the multiplication of risk probability and consequences. Others agree that priority should be established for every task, and the buffer size determined on the basis of the relative current risk to the project (Robinson and Richards, 2010, Fallah et al., 2010). The safety time should be removed according to the measured uncertainty of each activity (Rezaie et al., 2009).

In addition to evaluating risk for each activity, the classification of activities into larger categories is suggested (Shou and Yao, 2002). The authors develop a buffer sizing method, which classifies the activities into four categories, from low to high uncertainty. This enables the creation of different sizes of buffers for different safety levels, different activities and chains, as well as different types of projects.

Further research in combining CCPM with risk was performed by Schatteman et al. (2008). They propose adding the elements of risk when estimating activity durations. The researchers state that it is beneficial to use "the best case duration, not the mean or median, and to apply the simulated impact, depending on risk factors." The risk quantification method, risk assessment and risk database offered by Schatteman et al. (2008), lead to defining an individual distribution for each activity's duration, and so increasing stability.

Other ways suggested by researchers to incorporate risk management into CCPM are to take into account: the risk preferences of the various stakeholders (Liu et al., 2009), the risk perception of scheduler (Min et al., 2009), the number of significant risks (Newbold, 1998), and process risk (Hejducki and Rogalska, 2005).

However, despite great interest in risk integration with CCPM, most software only incorporates the risk of individual activities into the buffers by using the difference between the safe and shortened duration (PPS, Aurora-CCPM, Lynx). Being Management 3 has an area allocated for risk annotation. Risks can also be identified at the task and project level through Sciforma 5.0's risk centre. CCPM+ has the option of applying the SSQ method for buffer sizing.

4.7. Activity duration

Following the CCPM methodology, the ideal way to aggregate the safety times would be to remove them from each activity, and to insert an aggregated amount at the end of the project. However, the cutting of safety time from each separate activity is not an easy task. People overestimate (or underestimate) by different degrees. There are no proven methods or empirical evidence on the amount to be reduced (Raz et al., 2003).

CCPM proponents deny the importance of estimation accuracy. They believe that positive and negative variations will even themselves out. They argue that there can be no accurate data for estimation of activity durations, as unquantifiable uncertainties always exist, and therefore no perfect schedule could be created (Steyn, 2002). Winch and Kelsey (2005) agree with Steyn, stating that planning for longer than 3 months is futile, that historical data might be not valid for the future and "stochastic modelling does not identify the cause of variation." Therefore CCPM proposes simply cutting 50% from the task duration, without considering the accuracy of the estimate.

However, the original proposal of CCPM to cut the activity duration time to 50% is often not the best case. In fact, this percentage has no justification. The decision is not always possible due to technological factors (for example, hardening of concrete). Indeed, there is no reasoning for cutting the estimations to 50% when the task is performed by mechanical apparatus (Rezaie et al., 2009). Moreover, it is sometimes not possible to reduce duration to 50% because of “organisational, resource and financial dependencies” (Hejducki and Rogalska, 2005).

Furthermore, researchers do not agree on the same type of activity duration distribution. Although PERT uses a skewed beta distribution and the right skewed distribution is accepted in general for activity distribution function, some scientists advocate a gamma distribution (Winch and Kelsey, 2005), others apply lognormal or triangular distributions, and others suggest using an exponential one (Blackstone et al., 2009, Cohen et al., 2004). The approximation of the beta distribution (normal distribution) is often applied due to its simplicity. Moreover, the duration estimates of different activities follow different probabilistic distributions. Additionally, even a single activity can have different distributions during the project execution (Herroelen and Leus, 2001). Finally, Herroelen and Leus (2001) and Rezaie et al. (2009) raise doubts about the validity of using the right skew distribution.

The median may also not be the best solution to the problem. Herroelen and Leus (2001) performed an experiment proving that the safest way in terms of on time completion and number of rescheduling operations, is to use the mean value for activity duration.

Considering the uncertain basis on which the 50% suggestion is made, researchers offer different solutions. One of the ways to overcome the shortcoming of CCPM is to apply Bayesian stochastic approximation (Cho, 2009). Furthermore, in cases of low uncertainty but possibly high human imprecision, an option is to use fuzzy numbers, not stochastic variables (Herroelen and Leus, 2005). Another suggestion can be borrowed from research in cost estimation - to use the direct fractile assessment method, which is said to be least biased and most reliable

(Kujawski et al., 2004). However, this method is very similar to PERT, which requires an input of several estimations by people. Therefore it might not be useful and applicable in practice. Finally, researchers suggest borrowing the contingency method from the financial sector and applying it to graph schedules (Hejducki and Rogalska, 2005).

Another method for making an estimate more accurate is the decomposition of a task into smaller elements. However, researchers agree that this is not an appropriate way of improving the reliability of an estimate (Busby and Payne, 1999). Decomposition increases possibilities of errors, creates too much work for analysis, and a false sense of confidence (Kujawski et al., 2004).

Other proposals are related to well-known traditional techniques. The estimating techniques for repetitive work should not be forgotten (Blackstone et al., 2009). The use of a learning curve or hierarchical estimation framework might be applied, the triangulation of methods used, or expert judgement and analogous estimating employed. Software for the calculation of activity duration on the basis of data from a project database has already been created (Shou and Yao, 2002).

The predictions could acquire a higher degree of precision by relating them to past experience or interaction with engineers and other project participants (Al Tabtabai et al., 1997). Information on activity durations is often available from databases of previous projects, or could be obtained from participants of previous projects, although the latter source of information is not as reliable as written documentation. However, often the appropriate historical data are unavailable (Bedford and Cooke, 2001). Furthermore, even people familiar with activities can be unsuccessful estimators (Tversky and Kahneman, 1974) as they usually tend to remember recent information and make errors due to bias. Moreover, estimates from previous projects have to be based on the same conditions, level and productivity of resources, and the same methods. This makes it very hard to apply historical data in practice. Estimators in the construction industry might use the data from the Building Cost Information Service, but according to Yang (2007), the possibility of determining the productivity of each working squad in the construction industry is very low. Furthermore, productivity rates have systematic and random influences. Although systematic influences could be considered, and estimates corrected taking into account the benefits of learning curve and average weather conditions, the random influences on productivity might be much more difficult to incorporate into an estimate. Finally, the estimate of duration is valid only if the same level of multitasking has been applied, which is similarly very difficult to evaluate in practice.

Nonetheless, the reduction of duration should be made with care. Being aware of the reductions in task duration, people might simply double the duration of the estimate in advance (Shou and Yao, 2002, Raz et al., 2003).

Estimations of durations are never perfect; therefore safety buffers should be added to protect the schedule and the due date. Unfortunately, although the shortening of durations must be related to the sizing of buffers as the safety time from a separate activity is transmitted to the buffers, literature focuses separately on either estimating the activity duration or optimising the buffer size (for example, Rezaie et al., 2009). However, activity duration should be combined with buffer sizing.

The situation in practice is totally different from the theory. Although many suggestions have been made by researchers, software applications require only the direct entry of the shortened duration (Exepron), or entry of the safe duration, from which the shortened duration is calculated by software applying the default (50%), or a manually entered percentage (Aurora-CCPM, Being Management 3, CCPM+, Lynx). Other software allows the calculation of the safe duration from the shortened one (PPS). Aurora-CCPM, PPS and Lynx allow entering different values on a task basis, thus allowing the shortened duration to be equal to the safe duration, and not contributing to the project buffer in the case of low risk activity. Sciforma 5.0, on the other hand, does not allow manually overriding the percentage of shortening the task duration. Interestingly, different software uses different terminology to describe shortened and safe durations: for example, low risk duration (CCPM+, PPS), aggressive (Aurora-CCPM), focused duration (PPS), aggressive but possible and highly probable (Sciforma 5.0).

Certainly, further research is needed to clarify if the practice of excluding the safety margin can be sustained. A valuable future investigation could be to combine the estimation of activity duration with traditional methods, or to enable the selection of activity duration distribution. Additionally, it is important to improve the activity duration estimations jointly with buffer sizing methods.

4.8. Buffers

4.8.1. Project buffer

The original 50% rule for project buffer sizing has received a lot of criticism by researchers. The assumptions of statistical independence, on which C&PM and RSEM are based, could be questioned (Raz et al., 2003). The durations of activities might tend to change in tandem, and the duration of critical chain and project will be affected (Long and Ohsato, 2008). This fact is neglected by both buffer sizing methods. In addition, the size of buffer should be dependent on the risk preferences of various stakeholders (Liu et al., 2009)

The early studies on the sizing of project buffers concentrated on a comparison of C&PM and RSEM. The certain advantage of the C&PM is said to be its simplicity and sufficiently large buffer. However, the 50% rule leads to excessive amounts of buffers needed (Herroelen et al., 2002, Schatteman et al., 2008). The reason for this is the linear procedure, which means that with increasing length of critical chain, larger buffers are obtained. Although Goldratt argues that the rule is valid for any environment, as “the buffer is a natural extension of the task time,” the situation of linear increase does not always bring benefits, as it creates larger than necessary project buffers, resulting in lost commercial opportunities. Herroelen and Leus (2001) demonstrated by a numerical example that RSEM performs more accurately than C&PM.

However, both methods have been criticised for being derived from pure mathematical procedures, and consequently being inconsistent with the nature of project management. In addition to buffer sizing methods related to risk described previously, different proposals have been made to overcome this disadvantage. One of them calculates buffer sizes taking into account the project type (Yang, 2007). Another suggestion considers confidence in resource availability, number of tasks on the critical chain, importance of delivery time (Newbold, 1998), technical and resource factors, randomness, and non-recurrence of project activities (Hejducki and Rogalska, 2005).

Many recent attempts to improve buffer sizing methods are based on fuzzy set techniques, rather than probabilistic methods, (Long and Ohsato, 2008, Min et al., 2009) which, it is claimed, overcome the insufficiency of historical data. An improved genetic algorithm is offered for determining the size of buffer (Zhao, 2010). Lambrechts et al (2008) develop a time buffer allocation and sizing heuristic, which accounts for consequences of longer than expected activity durations caused by the resource breakdown.

Recent studies on how to determine buffer size focus mostly on particular situations, scenarios and schedule characteristics. They suggest different factors should be considered. One of the methods proposed is determining the size of buffer by considering the "number of activities in the chain, the uncertainty of activity duration and the flexibility of activity start time" (Yang et al., 2008). Other factors taken into account during the development of the sizing model, are "frequency of updates, task uncertainty and project service level" (Stratton, 2009). One more improved method of buffer sizing was developed by Liu et al. (2009), which considered flexibility and weight factors of an activity position in a network. Furthermore, resource tightness (demand compared to availability of resource) and network complexity (number of precedence relationships divided by the total number of tasks) are significant elements which should not be neglected, and are incorporated in the proposed adaptive method, with parameters of resource tightness and density (Tukel et al., 2006). Researchers also suggest determining the size of the buffer according to the average time and standard deviation of the most critical chain (Rabbani et al., 2007). Finally, buffer size should account for estimation errors or bias (Trietsch, 2005b), and should be based on data from previous projects as well as the ratio between the cost of earliness and the cost of delay (Trietsch, 2005a).

Current research goes even further, stating that buffer sizing should be dynamic, especially when new information is available, as constantly revised buffer sizes may point to new possibilities in terms of shortening the project duration. Fallah et al (2010) create an algorithm which determines buffer size dynamically.

The danger that buffers might fail to protect the project due date still exists (Herroelen et al., 2002), and more advanced methods should be incorporated into CCPM. There is little attention paid to buffer sizing in situations where several activities are influenced by the same factors. Additionally, as far as known, there has been no research done into the usage of buffers in real life situations.

While the sizing of the project buffer is one of the main topics among researchers analysing critical chain, software developers seem to ignore research and apply the simple original rules, or derive their own ways to size the project buffer. Exepron uses C&PM for buffer sizing, Being Management 3 suggests using 50%, but the percentage can be overwritten manually. Lynx allows entering the desired percentage, and the size of buffer can be adapted individually, taking into account the results of scientific analysis in combination with the judgement of project managers and the team. In addition to the possibility of entering the percentage, CCPM+ allows the use of the SSQ method, or combining a percentage and SSQ. Sciforma 5.0 applies the percentage of removed safety, the percentage of duration, or the sum of squares method for buffer sizing. Aurora-CCPM lets the user choose one of the following buffer sizing options: a) enter percentage sum of aggressive durations; b) RSEM; c) half sum of safe aggressive duration differences. Prochain has developed a new way to size the project buffer. The project buffer in “standard mode” consists of task variability and integration risk components. The variability component includes some percentage (50% or any other entered percentage) of the difference between the safe and shortened duration, multiplied by the maximum variability across all chains of tasks feeding the project endpoint. The amount of integration risk protection in the project buffer is very dependent on the structure of the network. Integration risk is determined by calculating the "average" completion date for the set of predecessor tasks, based on the needed protection time. The more or riskier the predecessors, and/or less available slack, the higher the values for integration risk. Although the integration risk algorithm is proprietary, ProChain claims that the duration of a project applying this methodology is often shorter than a traditional one.

4.8.2. Resource buffer

There seems to be no research done on the size of the resource buffer, and therefore no guidelines on resource buffer sizing exist. The only advice given is to size the buffer depending on the time of warning needed and the availability of resource. Moreover, it is not clear if a warning or safety time should be given for all resource units when several of them are available for the same resource type. Additionally, human resource may intend to use its additional slack, and the resource buffer might create resource conflicts. Another problem is that non-renewable resource (money, energy), spatial resource, double constrained resources (restricted per period and per total time horizon) are not considered. In risky situations, it may be appropriate to include financial incentives in subcontracts, such as paying for early delivery, penalties for later delivery, or paying for standby time.

However, as far as known, no research has been done to try and solve any of the aforementioned problems. The only suggestion found in scientific literature was to replace the resource buffer by a notice of upcoming tasks (Stratton, 2009). This is clearly not enough to solve the discussed issues, as this does not address the critique. Additionally, there seems to be no common agreement by researchers as to whether resource buffers are still being used, as some of the recent articles still mention them alongside project and feeding buffers (Bevilacqua, 2008, Zhao, 2010), while others completely ignore the original idea of a resource buffer. Future research would benefit from addressing the underresearched questions of resource buffers.

Surprisingly, a very similar situation observed in software products. The only software which still use resource buffers are Agile CC, Lynx and Sciforma 5.0. However, all of them apply resource buffers to stagger projects in a multi-project environment, where it should be called a capacity constraint buffer rather than a resource buffer. All other software developers decided to eliminate resource buffers from the newest versions of their products, one of them stating: "We have found schedule update meetings are a better way of communicating the same kind of wake-up call" (ProChain, 2011). However, the issue of having resources available is crucial to project completion on time. In fact, a survey shows that 87% of respondents in construction companies in Singapore add time buffers between the promised and the required date of major equipment to protect the schedule (Yeo and Ning, 2006). Furthermore, to ensure the possibility of starting an activity earlier than planned, not only resource buffers from the time perspective, but also resource buffers from the additional stock perspective should be analysed. Unfortunately, both CCPM software and researchers seem to ignore the problem of resource buffers.

4.9. Implementation

Raz et al (2003) assert that successful cases of CCPM implementation are not proven yet, as successful companies did not have strong methodologies before implementing CCPM. In fact, there have been a number of failures to implement CCPM in practice (Lechler et al., 2005).

The analysis of an unsuccessful case could be useful. Cases and survey research of CCPM application are still limited. There are some very brief video case studies, provided by CCPM software developer, Realization Inc. However, they provide only an introduction to successful case studies, thus concentrating more on selling their services rather than objective truth.

4.10. Subcontractors

CCPM chooses subcontractors on a basis of the lowest cost and their productivity, and offers incentives for higher productivity. The basis for offering incentives is the higher costs of delay compared to the financial incentive. Financial incentives promote partnerships with contractors, and increase business opportunities as “incentive contracts and alliances have been considered a key to success recently” (Raz et al., 2003). Together with incentives, penalties might be applied.

However problems arise, as not all projects have a right to offer incentives; for example government contracting. Moreover, there are ethical-cultural issues around prioritising projects on a basis of incentives which are not discussed by CCPM researchers.

Researchers have raised the problem of communicating and signing contracts with stakeholders when milestones are eliminated. However, the problem seems to be non-existent, as none of the software applications eliminate milestones from their schedules.

4.11. Monitoring

Buffer management by fever charts has attracted some criticism. Buffer management fails to take into account basic statistical process control (Trietsch, 2005a). It is also “not clear how much buffer should be allocated to each merging task “(Raz et al., 2003). There is no proof by scientific methods that only project buffers need to be monitored, eliminating feeding buffers. One more problem relates to the management of buffers, and whether to give priority to tasks on the previously defined critical chain which might have changed during project execution. However, the minimum slack rule could be used to overcome the last shortcoming of CCPM buffer management (Cohen et al., 2004). The question of how to forecast expected variations in control parameters remains. Although no research has been done specifically to forecast variations in a CCPM based schedule, the research done by Al Tabtabai et al (1997) could be useful to incorporate into CCPM. This research proposes using regression analysis and artificial neural networks to “capture the subjective forecasting process.” Nevertheless, additional research for an early warning mechanism is still required (Herroelen and Leus, 2001).

The software products use fever charts with straight lines (Exepron) or allow the entering of threshold percentages (Agile CC, Aurora-CCPM). Lynx allows entering the percentage of expected buffer consumption. Usually the software has an option for showing tasks which have the highest impact on the project or feeding buffers (Aurora-CCPM, CCPM+, PPS, Sciforma 5.0). PPS measures the impact based on a sensitivity value.

5. Human behaviour

Through analysing literature, it can be seen that the topic of human behaviour is almost exceptionally considered as an advantage of CCPM. It is argued that CCPM overcomes the disadvantages caused by multitasking (working simultaneously on several activities, thus delaying the end of each activity), and human nature to overestimate activity durations.

Multitasking

Although proponents of CCPM identify multitasking as one of the reasons why projects are late, some researchers disagree with the need to avoid multitasking, stating that multitasking creates necessary and beneficial conditions to link one project with another and share ideas between them (Reinertsen, 2000). Also, multitasking “reduces queuing problems and associated delays” because shared resources can be adjusted to resource demands which change in time (Reinertsen, 2000). However, situations may arise when human resources cannot be shifted from one project to another, due to their unique expertise and specific knowledge.

Multitasking is related to activity splitting. Some authors (Gray and Larson, 2006) even use it as a synonym, and state that multitasking is used to create a better schedule with more utilised resources. However, some activities cannot be split for technical or safety reasons.

Moreover, critics emphasize that care should be taken while eliminating multitasking. Only inappropriate multitasking should be avoided. Trietsch (2005a) presents an example of “good” multitasking: three projects wait for managerial approval to proceed while the manager is working on another activity. Should multitasking be avoided in that case?

The general rule, combining the views of both the proponents and the opponents of CCPM, should be: use multitasking with care. The objective basis of the appropriateness of multitasking could be an interesting field of future research.

Most of the software applications do not allow multitasking and activity splitting (CCPM+, Exepron, Lynx, and PPS). Sciforma 5.0 allows activity splitting, but this is not recommended. Only Aurora-CCPM has the option to tick if the job is interruptible, which is used if the schedule can be shortened.

Overestimation

CCPM proponents often assume that people overestimate durations while planning. However, there is no agreement amongst CCPM researchers about the optimism-pessimism point of view. People with an optimistic view expect the most favourable situation and tend to underestimate, while the pessimistic view leads to overprotected activity durations. Many supporters of CCPM deny the existence of optimism bias in estimating activity durations. Its opponents (Raz et al., 2003) refer to the lack of empirical data to prove the validity of assumptions concerning overestimation of durations. Critics note that not all people overestimate, as some might have optimistic evaluations leading to shorter than necessary durations. The proof of existing optimistic human behaviour has been discussed by many researchers (Busby and Payne, 1999, Son and Rojas, 2011, Russo and Schoemaker, 1992, McCray et al., 2002, Kujawski et al., 2004).

Proponents of CCPM identify the reasons for inflating initial estimates: accountability for your own estimate, and the later reduction of the estimate by other people due to different pressures. However, they neglect the fact that there are also significant reasons for underestimation of activity durations.

Observations and interviews by Busby and Payne (1999) revealed several underlying reasons for underestimating the activity duration. One of them was the fear of losing employment if the contract is not won. The other reason was pressure from other people to define low estimates for the whole project in order to win the contract. Other factors leading to over optimistic estimates are lack of experience or intensive competition. In addition, Busby and Payne (1999) point to the human characteristic of having overconfidence in our own abilities, and underestimating the time necessary to complete an activity ourselves, whilst the time necessary for others to complete a task is usually more realistically estimated.

Moreover, different people over or underestimate by different amounts. Given the same task, different people might give different durations. The amount of over or underestimation depends on risk attitudes, which in turn are dependent on the knowledge and experience of the estimator, and the political and economic environment (Wang, 2011). Estimation also depends on the intrinsic motivation (enthusiasm to finish the task as early as possible) or extrinsic motivation (money or other kinds of reward, threat of punishment or other coercion) (Wang, 2011). Optimism/pessimism bias is related also to project type and environment (Kujawski et al., 2004). For example, in the environment where the late finish of an activity or project is unacceptable, people tend to be pessimistic while estimating durations. However, as management knows about the pessimistic estimations in these environments, they usually cut the initial values of durations when setting deadlines, which leads to unused schedules.

In addition to optimism and pessimism during estimation, there are other limitations of human judgement abilities. People usually “rely on heuristics or rules of thumb” to make estimates (Tversky and Kahneman, 1974). Surveys show (Winch and Kelsey, 2005) that most informants do not consider the documented duration in a tender, but define their own estimate for project duration for internal communication and control. In most cases this estimate is longer than that documented in a contract.

They might rely on historical data or knowledge of estimators, but many of them are confident only in their own experience (Winch and Kelsey, 2005).

Tversky and Kahneman (1974) describe availability and anchoring heuristics. The availability heuristic is associated with addressing information about a particular event which just comes to mind, irrespective of the real frequency of event occurrence. People usually remember data which they are more familiar with. Due to biases they tend to over or underestimate risks and durations. Anchoring heuristics show that people usually stay close to the initial estimate, and therefore do not sufficiently adjust historic or initial data. This also refers to the fact that "people tend to overestimate the probability of conjunctive events and to underestimate the probability of disjunctive events" (Tversky and Kahneman, 1974). As a project is a series of conjunctive events, people tend to be optimistic about the probability of finishing on time. While evaluating risks (disjunctive events), they are more likely to be pessimistic. Confirmation bias (Son and Rojas, 2011, Watson, 1960) is associated with the human tendency to look for supporting data, but to ignore conflicting information.

All of the described biases lead to insufficient safety times (loss making business) or excessive safety times (lost business). Unfortunately, research (Tversky and Kahneman, 1974) showed that human judgement cannot be controlled by motivating people to provide an estimate which is as accurate as possible neither by financial rewards, nor by penalties. Collective estimating could reduce optimism bias, but not completely (Son and Rojas, 2011).

Nevertheless, bias and human nature to apply rules of thumb must be considered while developing a baseline plan. CCPM might work well when durations are overestimated. However, it could be a complete catastrophe if the schedule was planned with an optimistic bias and then CCPM applied. When a schedule is compressed by 50%, then human resources are reduced by half and the budget decreased. Therefore the reduction of activity duration should not be done automatically; in an already optimistic schedule this could be disastrous.

The precision of activity duration estimation is important, as mistakes can lead to incorrect information about financial outcomes (Dursun and Stoy, 2011). Therefore objective prediction of project duration is one of the key factors for project success (Dursun and Stoy, 2011). Moreover, the predicted durations and accuracy of schedules serve not only as a tool for financial planning and monitoring, but also for litigation issues (Skitmore and Ng, 2003, Trauner, 2009).

CCPM software Lynx creates a database of time recordings to assess the level of under or overestimating as input for improving the estimations of similar work. However, otherwise most of the described research on bias is not considered by both CCPM researchers and is not incorporated into CCPM software.

6. Conclusions

The literature review of CCPM in a single project environment revealed many unsolved problems. The overestimation bias, issues related to resource buffers, and assumption of independent activities are not considered by researchers. Additionally, it seems that researchers just analyse separate parameters, and are not very familiar with the methods developed by others or used in real life situations by implementers. Even if some of the suggestions for improvement are made, they are not taken into account for further research; new suggestions and ways to improve CCPM are offered instead. This is the case for research on sizing project and feeding buffers, shortening activity duration, rescheduling, methods for determining the critical chain or defining priority for tasks, and integration of risk into CCPM. The comparison and consolidation of different suggestions in these fields of research is a valuable area for future research. The need for research on problems with human factors and the motivation of subcontractors has been identified during the literature review. However, these research areas could learn much from the sciences of communication, sociology and psychology. A joint research project with experts in these fields could indeed lead to a significant contribution to knowledge and improvement of CCPM.

The analysis of software products showed a similar lack of attention to the assumption of independent tasks, resource buffers and human bias. More research on these questions might influence the concern of software developers. It could be worthwhile for researchers to investigate the ways software determines critical sequence. On the other hand, the vast amount of existing research on rescheduling, shortening of activity duration, risk integration, monitoring, sizing of project and feeding buffers, could bring significant benefits for practitioners. The reasons why a number of suggested beneficial algorithms are not incorporated into the software applications need more investigation. Insight into this problem could also provide valuable knowledge for researchers, both in the field of CCPM or any other scheduling and planning environment.

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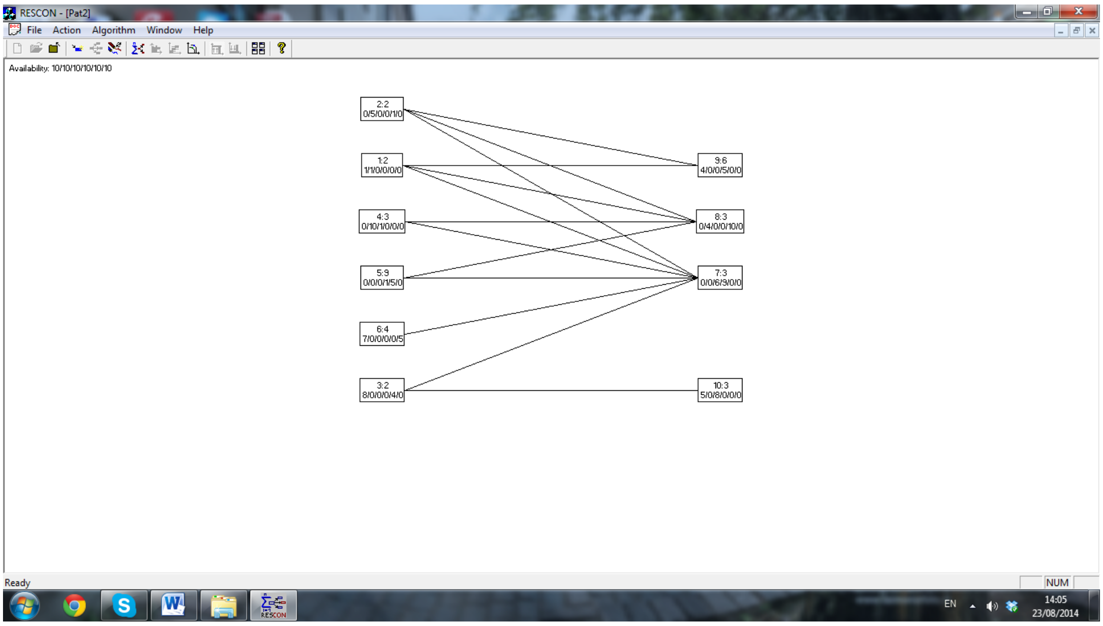
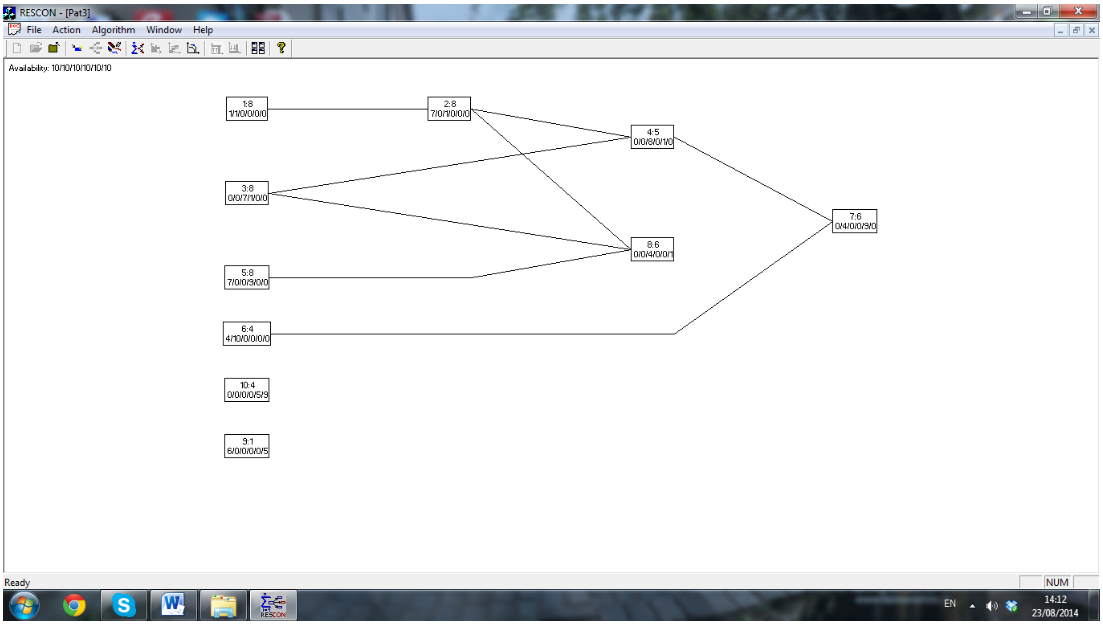
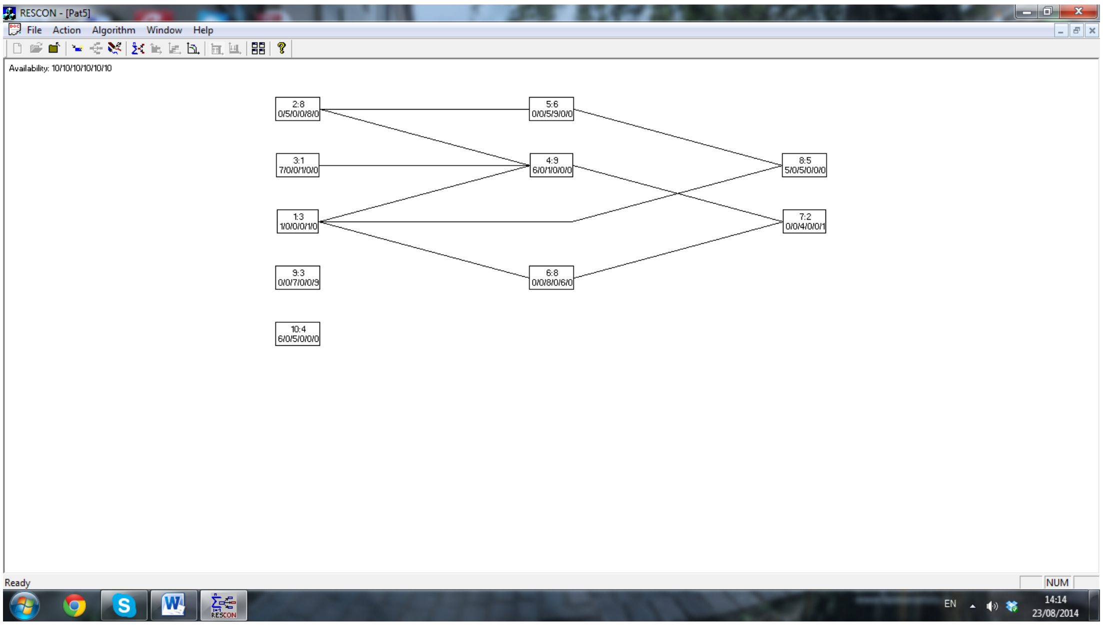
Appendix B: Projects, generated by RanGen



Project No. 1



Project No. 2


RESCON - [Pat5]
File Action Algorithm Window Help
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2:8
0/5/0/0/8/0
3:1
7/0/0/1/0/0
1:3
1/0/0/0/1/0
9:3
0/0/7/0/0/9
10:4
6/0/5/0/0/0
5:6
0/0/5/9/0/0
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6:8
0/0/8/0/6/0
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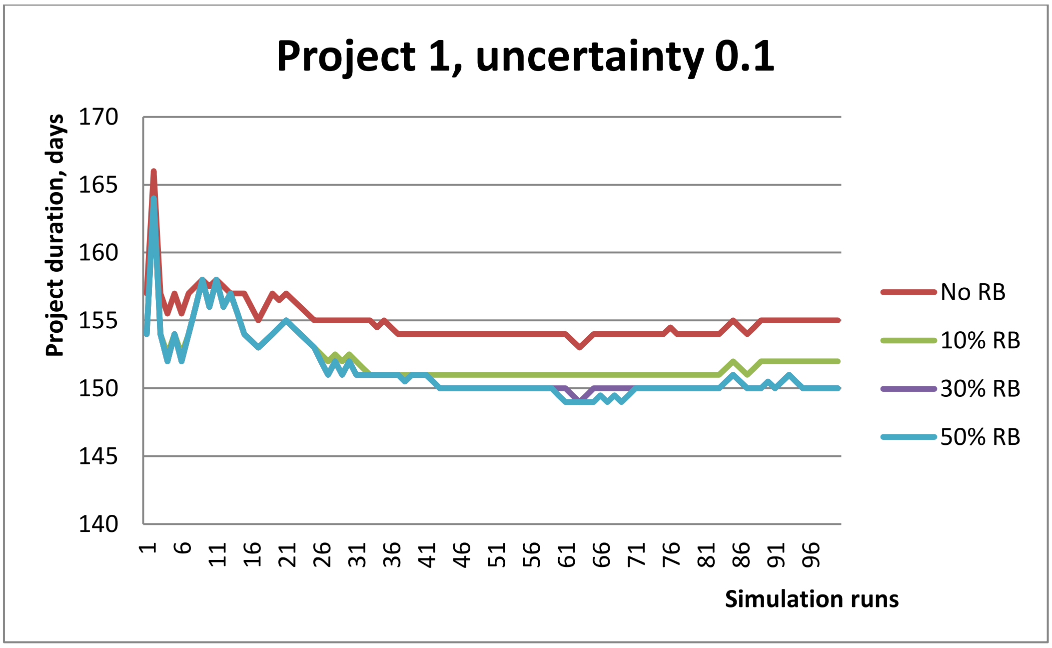
7:2
0/0/4/0/0/1
Ready
NUM
EN
14:14
23/08/2014

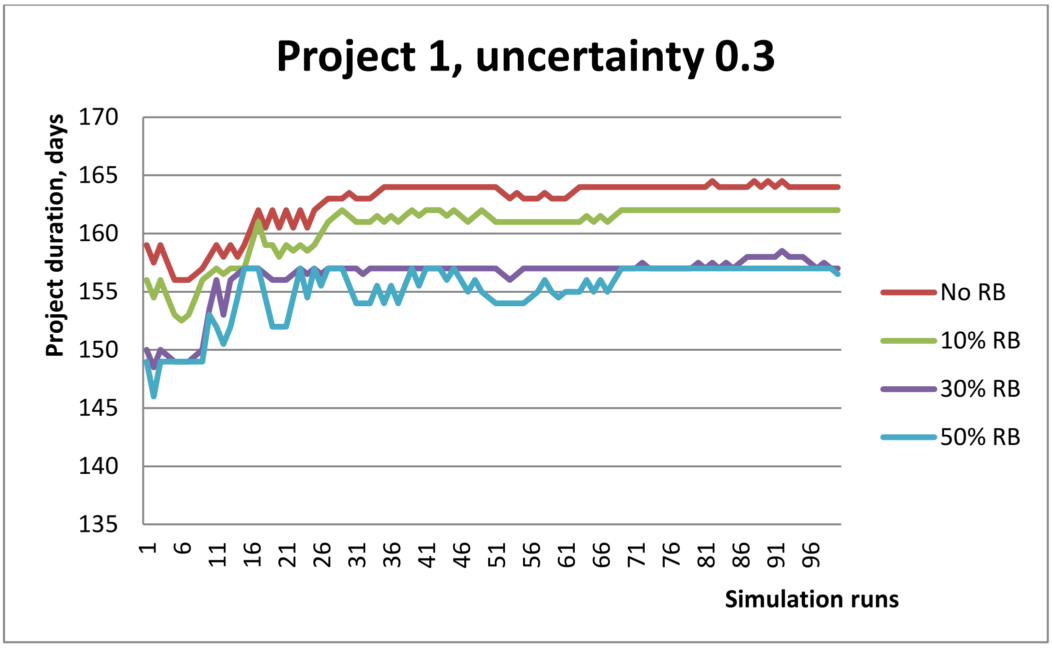
Project No. 3

Appendix C. Cumulative moving medians of all projects

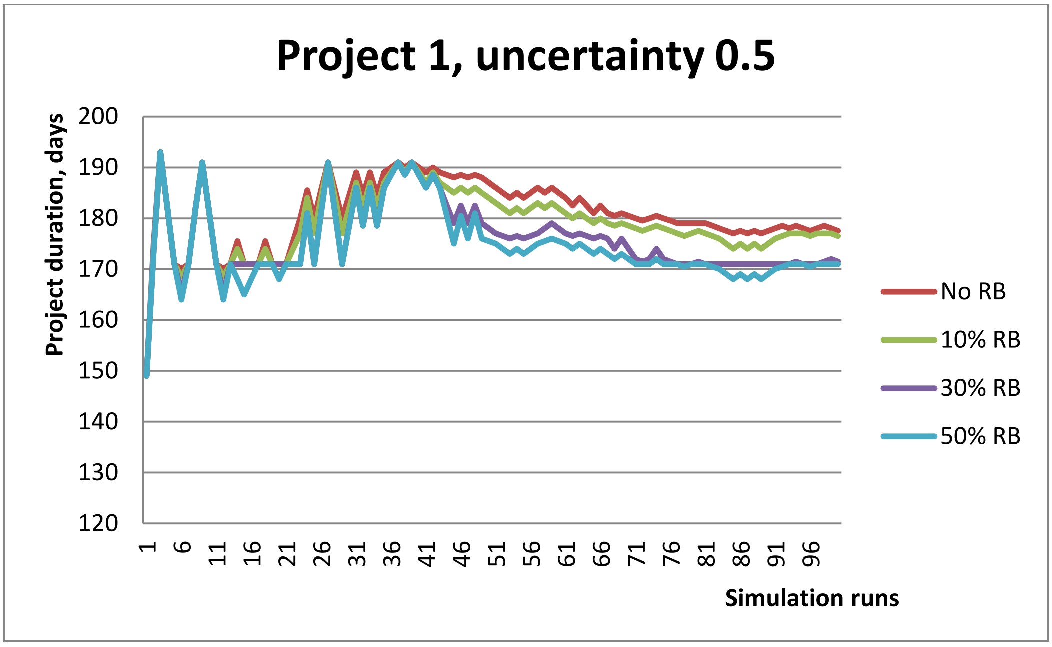
Project 1, Uncertainty 0.1



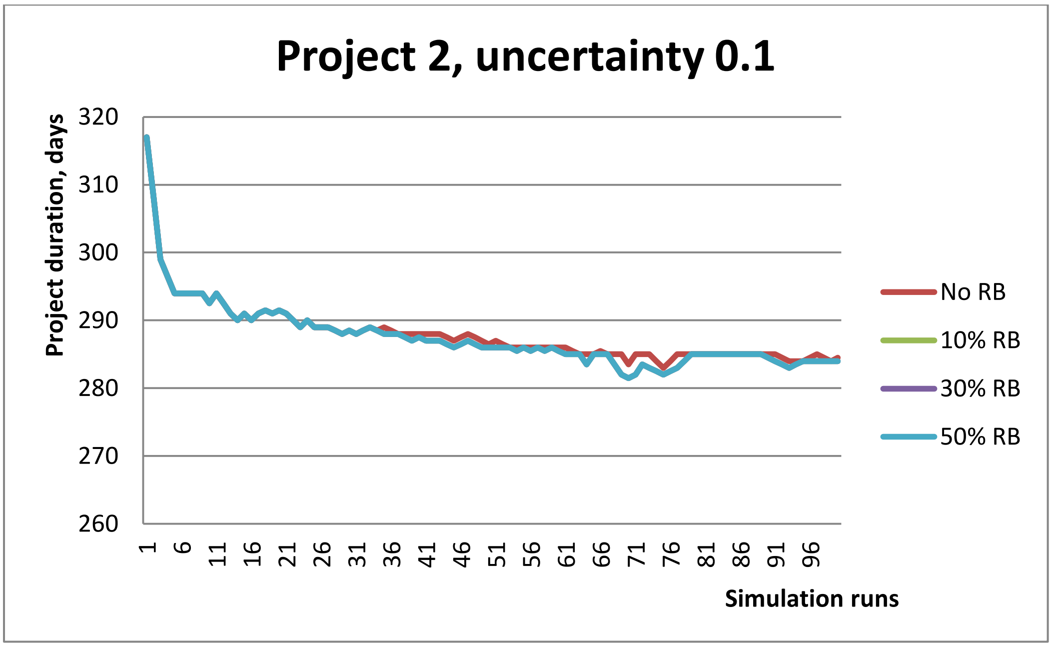
Project 1, Uncertainty 0.3



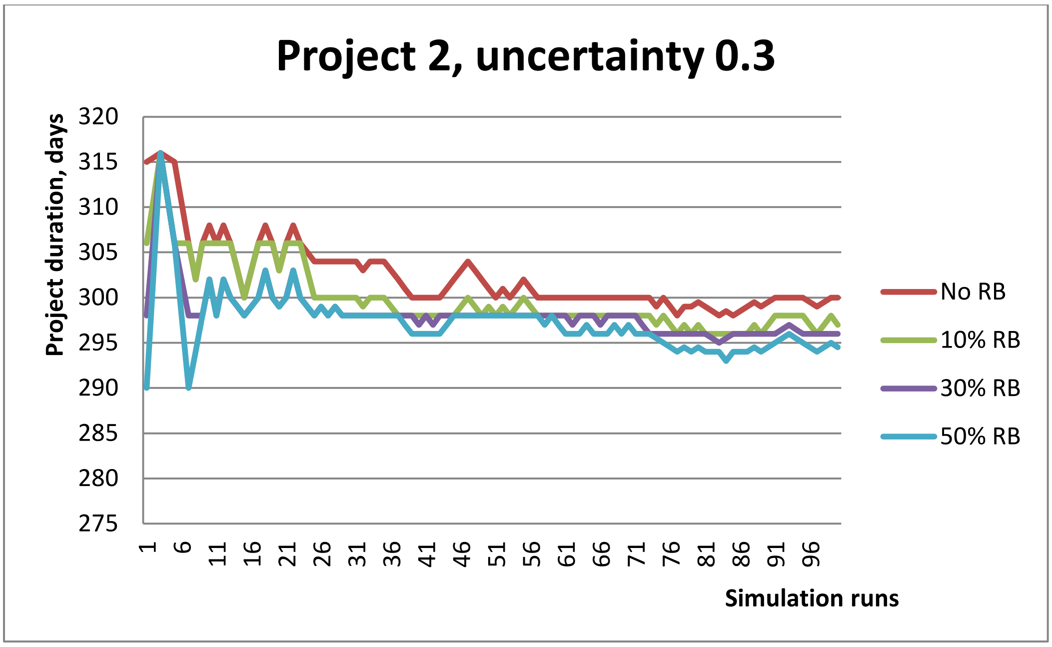
Project 1, Uncertainty 0.5



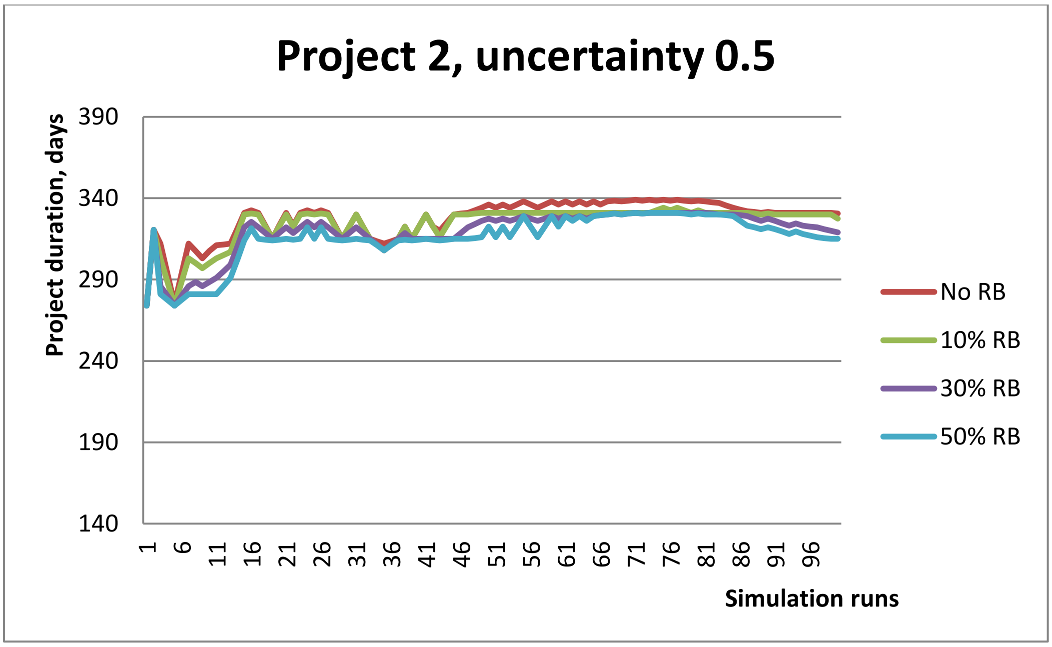
Project 2, Uncertainty 0.1



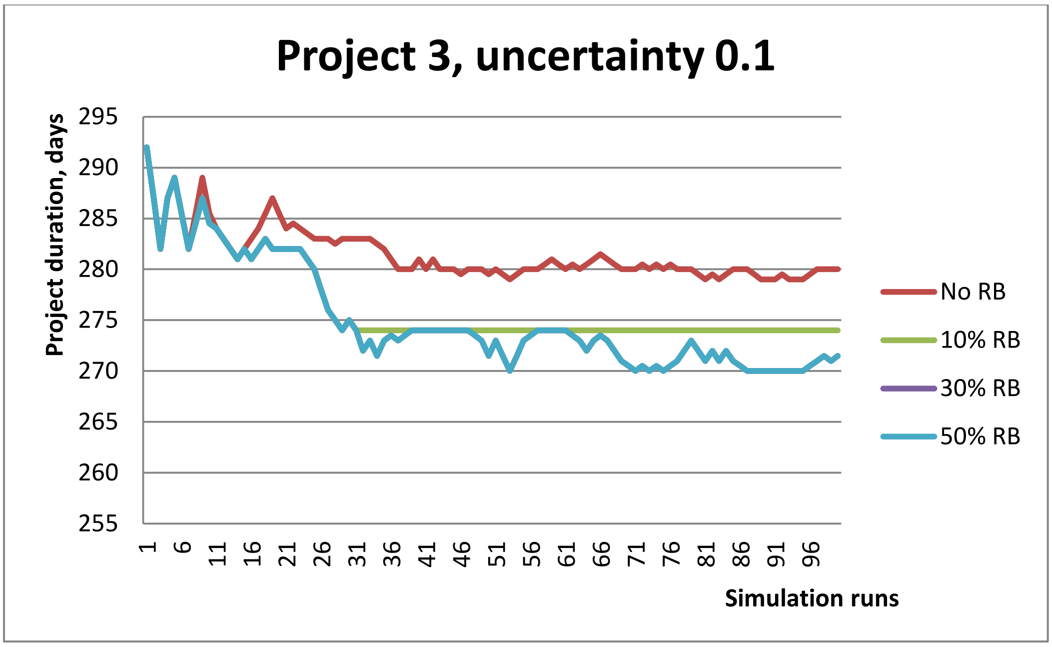
Project 2, Uncertainty 0.3



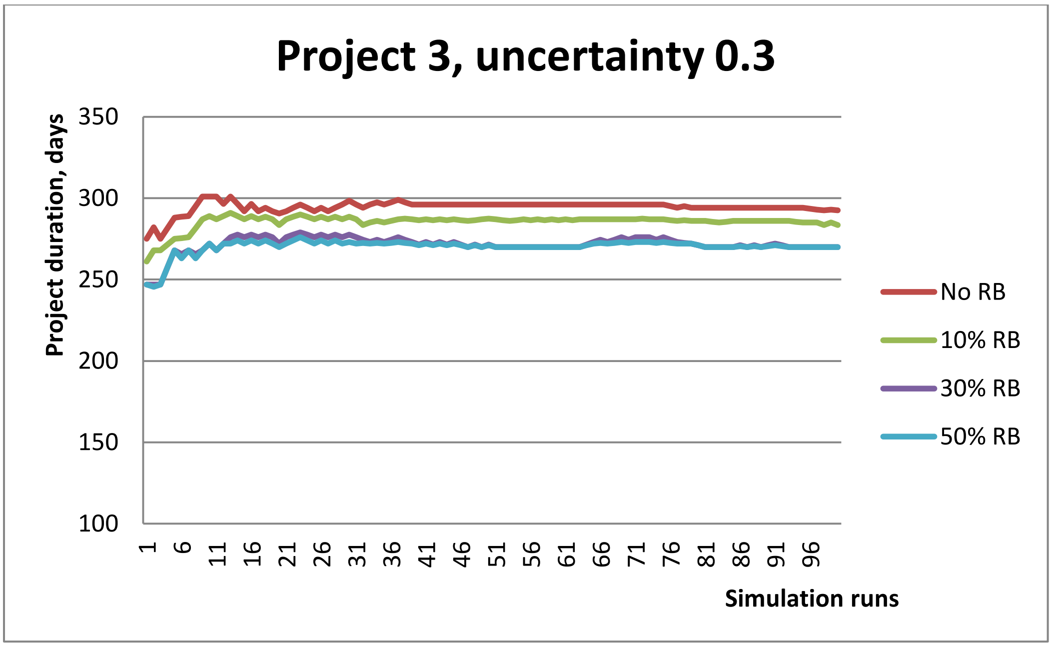
Project 2, Uncertainty 0.5



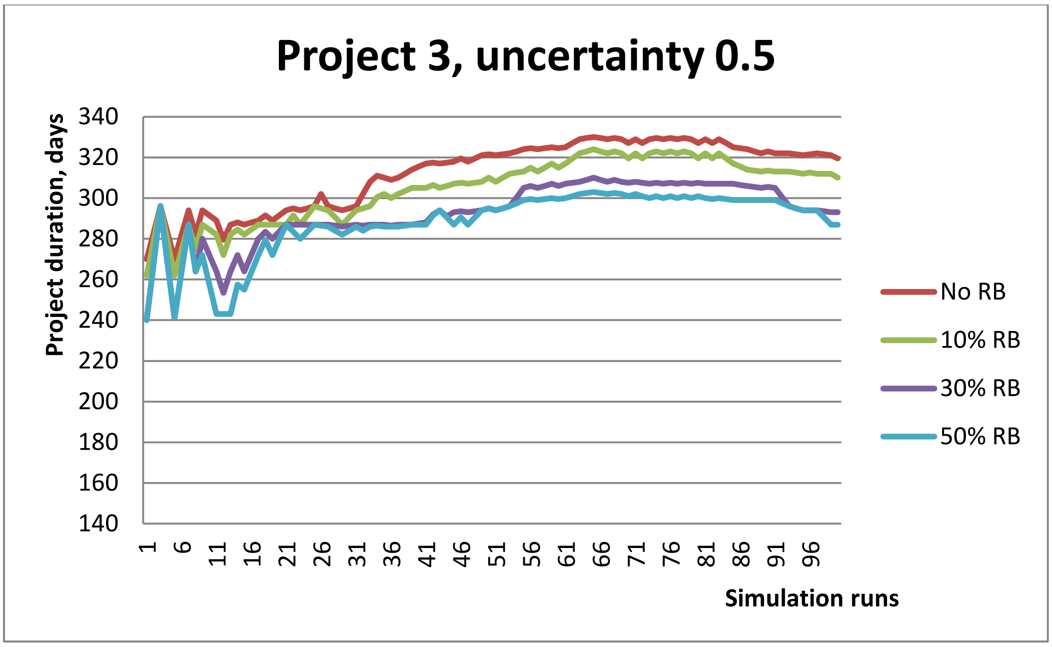
Project 3, Uncertainty 0.1



Project 3, Uncertainty 0.3



Project 3, Uncertainty 0.5



Appendix D: Example of Critical Chain Project Management network development

This appendix presents an example of Critical Chain Project Management schedule of how resource buffering might be applied. The same network is used as on page 166, Chapter 5.2. The Gantt chart of the network is repeated below.

The critical chain in this example consists of activities 1, 2, 4, 5, 7 and 8. Following the CCPM methodology, feeding and project buffers have to be inserted first. Feeding buffers are instered at the point where non critical activity joins critical chain. For example, activity 3 is a non critical activity, which has to be finished before the critical activity 4 can be started. Therefore, feeding buffer is inserted between activities 3 and 4. The other feeding buffers are added in the same way.

Project buffer is always inserted at the end of the project.

The size of feeding and project buffers depend on the method chosen. There are a number of proposals described in this thesis to determine the size of buffers. In the simplest Cut&Paste method, half of the project duration has to be entered as a project buffer. For example, if project duration is 100 days, project buffer should be equal to 50 days.

This thesis proposed to insert resource buffers at the point where a new resource is performing an activity on a critical chain. For example, activity 2 is performed by resources A and C. A has been previously working on activities 1 and 5. For this reason, no resource buffer for resource A is needed at this point. However, resource C is a new resource on a critical chain. Therefore, a resource buffer 1 is inserted before activity 2. Following the same logic, resource buffer 2 is inserted before activity 4 for resource E. Resource buffer 2 also includes resource C. Although this resource has been working on a critical chain before, the demand for it was only 10%. The critical chain activity 4 needs 80% of the resource C. Because of that, the resource buffer 2 for 70% of resource C is added. In the same way, other resource buffers are added to the schedule.