

Current Status and Future Potential of the Research on Critical Chain Project Management¹

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Abstract

Critical Chain Project Management (CCPM) is a relatively new method which introduces a new mechanism for managing uncertainties in projects. A high number of studies on CCPM have been published and it seems it is now time for an extensive review. This study consults the CCPM literature in an inductive manner in order to answer the following questions: Is ongoing research being conducted on CCPM or has it lost its popularity among researchers? What have been the different approaches towards CCPM in the literature and what has each of them contributed to the knowledge area? What improvements have been made to the method since its introduction in 1997 and have these answered the critiques of the method? In what direction should future research be directed and what are the potential areas of CCPM for further development? The main aim is to describe the current status of research on CCPM and explore CCPM aspects that require more research. This study covers 140 journal and conference papers written on CCPM through an “exhaustive with selective citation” approach identified through online and reference searching. Those papers are categorised into six groups of introductory, critical, improving, empirical, case-reporting and exploiting papers, using the “hierarchical coding” method. As the result of this, the current status of research on CCPM is critically reviewed, themes are identified and 21 areas for future investigations are recommended that mostly need operational research analyses.

Keywords: Critical chain, Project scheduling, Literature review, project management.

JEL: O21, O22

Introduction

Critical Chain Project Management (CCPM) was first introduced by Eliyahu Goldratt as a new method of managing projects at the International Jonah Conference in 1990 (Bevilacqua et al., 2009). It remained unexplored until he decided to repeat his success in writing “The Goal” business novel in 1984, this time with “Critical Chain” in 1997. In his book, Goldratt extended the principles of the Theory of Constraints (TOC) to project management. TOC was based on the principle that every system has a constraint that prevents it from reaching higher levels of performance and the only approach to improve the system performance is to enhance the capacity of that constraint. With regard to CCPM, this unique constraint in single project environments is the longest chain of activities in the project network, taking into account both activity precedence and resource dependencies (critical chain) and in multi-project environments

¹ *Second Editions are previously published papers that have continued relevance in today's project management world, or which were originally published in conference proceedings or in a language other than English. Original publication acknowledged; authors retain copyright. This paper was originally presented at the 4th [Scientific Conference on Project Management in the Baltic States](#), University of Latvia, April 2015. It is republished here with the permission of the author and conference organizers.*

is the resource impeding projects' earlier completion. Goldratt (1984, 1997) provides a 5-step procedure for the process of ongoing improvement (identify the constraint, exploit the constraint, subordinate other non-constrained entities to the constraint, elevate the constraint, return to step one if the constraint is changed). CCPM also suggests estimating activity durations to their 50% probability of being completed on time and consider a buffer (project and feeding buffers) at the end of each chain of activities to allow for uncertainties. There are also some other buffers, namely resource buffer, drum buffer, capacity buffer and cost buffer. Some other characteristics are that it is completely against multitasking, does not consider activity due dates and schedules non-constraint activities to their latest start.

CCPM is not a holistic approach towards managing projects and is more a scheduling method addressing schedule-related aspects of projects. It only includes human aspects in terms of scheduling activities and not related to leadership, project governance and communication. These aspects should be addressed through TOC philosophy or Lean principles, as explained in the TOC Handbook (Cox and Schleier, 2010). As it is outside the scope of this study to explain in more detail the principles of CCPM, readers are encouraged to read the CCPM classic book by Leach (2014) for a comprehensive explanation.

Methodology

Since its introduction in 1997, CCPM has been the subject of a large number of studies. This study aims to describe the current status of research on CCPM and explore CCPM aspects that require more research in the future by means of a literature review in order to identify different approaches towards the method, avoid reinventing the wheel by studying existing knowledge, gain methodological insights and differentiate between what has been done and what needs to be done in the future. To achieve this aim, this study answers the following questions: 1. Is ongoing research being conducted on CCPM or has it lost its popularity among researchers? 2. What have been the different approaches towards CCPM in the literature and what has each of them contributed to the knowledge area? 3. What improvements have been made to the method since its introduction in 1997 and have these answered the critiques of the method? 4. In what direction should future research be directed and what are the potential areas of CCPM for further development?

To address the mentioned aim, this study conducted an extensive literature search through an "exhaustive with selective citation" approach meaning that it only included journal and conference papers (Cooper, 1988). These types of sources, because of their reviewed nature, are able to provide more reliable and valid discussions on CCPM.

Online search facilities were used to identify the maximum number of sources containing one or more of the following keywords generated from a relevance tree: critical chain, Goldratt, buffer management, fever chart, time buffer, cost buffer, resource buffer, project buffer, feeding buffer, drum buffer, capacity buffer, drum resource, capacity constrained resource, buffer sizing, Parkinson's law, Murphy's law, student syndrome, project scheduling, theory of constraints, roadrunner mentality, relay race work ethic and multitasking.

As the online search, based on keywords, only identifies a small percentage of all available sources (Randolph, 2009), the reference lists of all papers were also analysed to find any remaining resources. Only papers where the main discussion was related to CCPM were selected

and others that merely mentioned it as an existing method without discussing it under an exclusive heading within their texts were ignored. Eventually, a total number of 140 English journal and conference papers were selected, from which 52 are conference papers mostly (41 papers) presented in conferences and symposiums organised by PMI and IEEE, 68 are academic peer-reviewed journal papers from 39 different journals (29 of these papers published in the well-known journals of International Journal of Project Management, Project Management Journal, International Journal of Production Research, Production and Inventory Management Journal and South African Journal of Industrial Engineering) and 20 are practice-focused reviewed journal papers mostly (12 papers) published in PMI's PM Network².

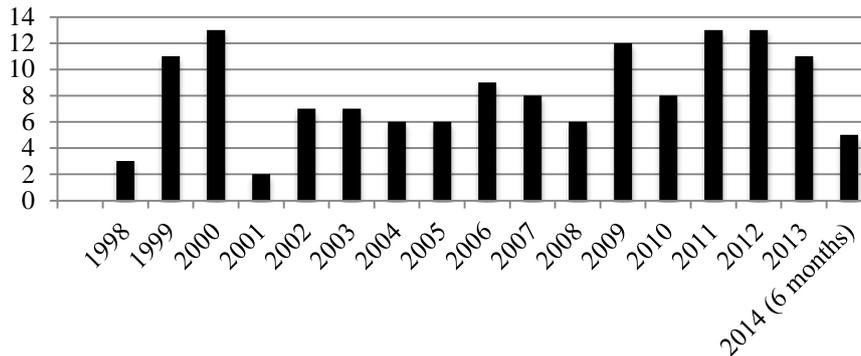
The full texts of all papers were analysed and coded based on the “hierarchical qualitative coding” method explained by Saldana (2009). As he explains in his manual, “a code in qualitative inquiry is most often a word or short phrase that symbolically assigns a summative, salient, essence-capturing, and/or evocative attribute for a portion of language-based or visual data. The data can consist of interview transcripts, participant observation field notes, journals, documents, literature, artifacts, photographs, video, websites, e-mail correspondence, and so on”. This method was used as a basis for categorising the literature and identifying the existing themes (“a theme is an outcome of coding, categorization, and analytic reflection” (Saldana, 2009)) in the CCPM studies explained in the following sections. After coding every single passage in all papers, they were categorised into six groups based on their position on CCPM: introductory, critical, improving, empirical, case-reporting and exploiting. Every paper, depending on the codes of its content and the subcategories, have been categorised in one or more of those categories. This study answers the above research questions using the information obtained from reviewing the CCPM literature in the following sections.

An Overview on the Literature

This section answers the first research question of this study. Figure 1 illustrates the distribution of all 140 CCPM studies considered by this paper. This bar chart represents the level of interest of researchers in CCPM between 1998 and the first half of 2014. As can be seen in the figure, there has been a sharp increase in the number of studies between 1998 and 2000. This is the period when the project management community was showing its first reactions to the introduction of CCPM and attempting to analyse its various aspects compared to traditional methods. The number of studies reached a maximum of 13 in 2000, a record that was only reached again in 2011 and 2012. In 2001, the number of studies plummeted to 2 and started an overall rise that continued until 2012. This sudden fall in number of studies in 2001 is probably because of the change in researchers' position on CCPM from introductory to improving and the need for more evaluation of the method that will be shown below (Figure 2). The number of studies again went down from 13 to 11 in 2013 and reached 5 studies in the first 6 months of 2014.

² See <https://www.dropbox.com/sh/7pww2luszyzjksm/AAAH0B3-DyZRY8XdoOFmCCWaa?dl=0> for more details about the selected papers.

Figure 1. Distribution of 140 CCPM studies between 1998 and the first half of 2014 (Author's own)



These changes show that an average number of around 8 studies have been conducted in every single year after the introduction of CCPM. The high number of studies published in recent years and those 5 studies completed in the first half of 2014 show that the subject is still under scrutiny of researchers and has not lost its appeal for them. This also indicates the potential of CCPM for more investigations. Answering each of the three remaining research questions of this study will provide reasons for changes in authors' interest in CCPM demonstrated in Figure 1.

Codifying, subcategorising and categorising the literature were conducted in order to answer the second research question of this study: "What have been the different approaches towards CCPM in the literature and what has each of them contributed to the knowledge area?". Six different approaches towards CCPM were identified to be introductory, critical, improving, empirical, case-reporting and exploiting.

Definitions of these approaches are provided as follows:

1. Introductory studies: those sources that provide an introductory explanation of CCPM basics and principles in comparison with traditional methods without advancing or criticising the theory and practice of the method.
2. Critical studies: those sources that provide a critical perspective on the practicality and feasibility of some or all the CCPM basics and principles.
3. Improving studies: those sources that enhance the tools and techniques of CCPM through adopting other existing methods or inventing new ones.
4. Empirical studies: those sources that attempt to enrich, compare, validate or invalidate CCPM principles or techniques through simulations, games or statistical analysis.
5. Case-reporting studies: those sources that report on implementation and deployment cases of CCPM.
6. Exploiting studies: those sources that apply CCPM principles to different project sectors and non-project work beyond scheduling.

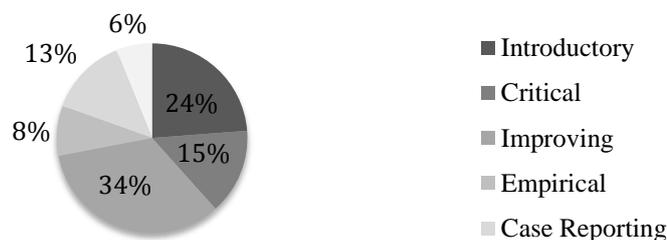


Figure 2. Illustrates the proportions of papers in each category (Author's own)

Following the above categorisation, it can be noticed from Figure 2 that the largest portion of studies on CCPM has been on improving its tools and techniques (34%) while the smallest belonged to exploiting CCPM in other sectors (6%). This shows that researchers have focused their best efforts on advancing the tools and techniques of CCPM. Despite this, it has not yet become practitioners' favourite project management method by any means (Repp and Wright, 2013). Moreover, introductory and critical studies have been the second and third most popular subjects among researchers with 24% and 15% of all papers respectively. Despite the need for more case studies on CCPM applications, case-reporting papers still constitute a small segment of the total (13%). Finally, 8% of all 140 studies have been written on evaluating the existing CCPM techniques – using games, simulations and statistical analysis.

In order to provide a better understanding of changes of the bar chart shown in Figure 1, Figure 3 shows the breakdown of number of studies between 1998 and the first half of 2014 for the introductory, critical and improving categories explained above. The other three categories were ignored because they have a much smaller impact on the numbers in Figure 1 as a result of their lower number of studies.

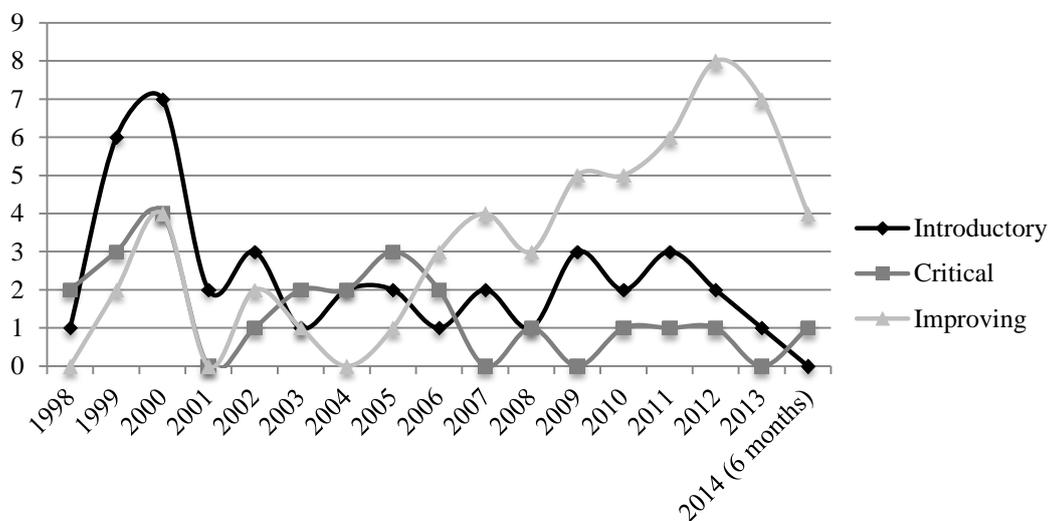


Figure 3. Changes of numbers of introductory, critical and improving studies between 1998 and the first half of 2014 (Author's own)

Looking at Figure 3 and comparing it with Figure 1, one would realise that the general trend is approximately the same in both figures (two peaks in 2000 and 2012 and a steadily rising number of studies in the middle). However, it is Figure 3 that helps us understand those changes more thoroughly. In the figure, introductory studies are the most popular in the early years of CCPM from 1999 to 2002.

As one would expect, researchers firstly attempted to introduce CCPM to the project management community during this time. This did not continue after 2003 although at least one introductory study was conducted in every single year until 2014. It is worth mentioning that introductory studies are still being published 17 years after the introduction of CCPM despite empirical data showing that the majority of project managers are aware of CCPM principles (Repp and Wright, 2013). Another important observation is the dramatic rise in the number of improving studies from zero in 2004 to 8 in 2012 that shows the attempt of researchers to

expand the boundaries of CCPM knowledge. Regarding critical studies, there is a general decreasing trend during the considered period of time that can be attributed to successfully overcoming CCPM weaknesses through time.

LITERATURE REVIEW UNDER SIX CATEGORIES

In order to answer the other half of the second question and the third question, each category of papers will be reviewed in detail in the following sections:

Introductory Studies

The main aim of these studies was to highly publicise CCPM in the early years of its introduction. Their authors normally had a positive approach towards CCPM by mentioning its benefits and advocating its deployment in organisations. They also attempted to gain recognition for CCPM as a possible substitute for traditional methods by the project management community and explaining its tenets. In addition, they paved the way for other more critical and improving studies in the future through precise clarification of CCPM principles and fundamentals. Some of the most cited introductory papers (out of all 39 studies) have been written by Leach (1998, 1999, 2001), Gray et al. (2000), Cervený and Galup (2002), Blackstone et al. (2009), Steyn (2000), Rand (2000), Rizzo (1999), Umble and Umble (2000), Hoel and Taylor (1999) and Patrick (1999a, 1999b). They cover a wide variety of subjects that were subcategorised and codified as follows:

- ***Issues with traditional methods from a CCPM perspective:*** task estimates based on 90% probability of completion, procrastination or student syndrome, Parkinson's law, Murphy's law, task convergence, task due dates, failure to report early task completions, loss of focus, railway scheduling, early start scheduling, rescheduling, resource dependencies, multitasking.
- ***CCPM principles:*** fundamental theories behind CCPM, 5-step continuous improvement process, single and multi-project scheduling using CCPM, buffer insertion and management methods, buffer sizing methods.
- ***CCPM benefits:*** task estimates based on 50% probability of completion (shorter tasks and eventually project durations), buffering the project and tasks against uncertainty in a strategic way, clear instructions for multi-project scheduling, built-in risk management, accommodating human factors of projects into the schedule, simple buffer management and project monitoring and control, encouraging early report of task completions (no due dates), roadrunner (relay race) scheduling, late start scheduling, no multitasking, less work-in-process (tasks waiting for resources to be performed) at any point in time, more throughput of the system and higher chance of finishing on time.

One of the issues with introductory studies is that they lack critical and practical analyses of the method and are not inclusive enough to discuss both advantages and disadvantages of CCPM. In addition to this, many of them do not include a literature review section and thus provide a weak contextual background. As a result, about 64% of introductory papers have been published in conference proceedings or practice-focused journals and have fallen short of academic journals' standards. Those that were published by academic journals usually also included empirical, critical or improving approaches. Another issue is that they mostly have a very restricted view

towards projects' success and failure by limiting them to projects' time performance only. This is while a project's scheduling or time performance is only one of many identified project success/failure factors and criteria (Ghaffari, 2014).

Critical Studies

Each time a new method is introduced for the first time, it will encounter some levels of resistance. This will trigger beneficial discussions that predominantly strengthen the novel method. This is the same for CCPM and critical discussions on the value and principles of it immediately started from the year after its introduction in 1997 (Figure 3). They (25 identified critical studies) have mostly encouraged critical thinking, recognised CCPM as an effective development of project management, identified its weaknesses and invited researchers to investigate means of overcoming them (e.g. McKay et al., 1998; Elton and Roe, 1998; Koskela et al., 2010; Cohen et al., 2004; Globerson, 2000; Herroelen and Leus, 2000, 2004; Raz et al., 2003; Herroelen et al., 2002; Lechler et al., 2005a; Wilkens, 2000; Ribera et al., 2003; Pinto, 1999; Millhiser and Szmerekovsky, 2012). There are also some others who believe that traditional methods have a satisfactory performance if implemented correctly and there is no indispensable need for adopting CCPM (e.g. Duncan, 1999; Zwikael et al., 2006; Trietsch, 2005a). In general, critical studies have benefited CCPM by preparing conditions for further development of its tools and techniques by authors of the improving studies.

A critical review of the critical and some complementary sources will be presented in the following sections that have been organised based on the codes identified in the process of coding the literature. This will provide a better understanding of the common topics discussed within CCPM literature and the groundwork for improving studies discussed later.

Is CCPM a New Method?

The introduction of CCPM in 1997 became the centre of a controversy between Goldratt and his proponents and some academics who believed that the CCPM principles are not novel to project management. They accused Goldratt of gathering together some existing concepts and introducing them as new ones using new terminology. Trietsch (2005a) has drawn some of the most severe criticisms of Goldratt's methods (from TOC to CCPM). He questions their originality and uses the term Management By Constraint rather than TOC. In his opinion, TOC is only a paraphrased form of the Just In Time principles already deployed all over the world.

Trietsch (2005a), in order to show that CCPM adds nothing new, adds a "zero" step to the CCPM 5-step continuous improvement process mentioned above and attempts to match each step to the stages undertaken in the CPM/PERT methods. Although he is successful in mechanically matching the steps of the two methods, he ignores some of the changes in the principles of CCPM such as the inclusion of human factors (student syndrome, Parkinson's law and no multitasking in the schedule) and benefits of considering resource dependencies in determining the critical path (raising awareness about resource constraints and giving the appropriate level of priority to real critical activities requiring the constrained resources when allocating them).

Trietsch (2005a) continues his critique by citing some of the concepts similar to the principles of CCPM that already existed in the literature at the time of CCPM introduction. He firstly

discusses the consideration of resource constraints in project scheduling. CCPM proponents claim that it takes into account limited resources in addition to activity precedence (Umble and Umble, 2000; Steyn, 2000; Leach, 1999); however, Trietsch (2005a) and some others (Herroelen and Leus, 2001; Millhiser and Szmerekovsky, 2012) believe that resource constraints have always been at the centre of attention since the emergence of CPM/PERT methods in the 1950s.

Trietsch (2005a) mentions Wiest (1964) who introduced the term “critical sequence” and Raz and Marshall (1996) who analysed the relationship of free and total slacks with resource constraints as two instances. Herroelen and Leus (2001) also added another example of precedent sources that developed a method for considering the critical sequence that includes resource limitations rather than the normal critical path. Trietsch (2005a) correctly argues that Goldratt has not cited these sources in his own work and has simply changed the name to critical chain. In his opinion Goldratt is an entrepreneur who does not value academic rules and practice, although an assumption is that this may be due to the inertia Goldratt encountered when he introduced his previous innovations in an academic style (Watson et al., 2007).

Secondly, Trietsch (2005a) criticises the rule of no activity due dates in CCPM. Although he admits the significance of due dates in project delays by citing the studies of Schonberger (1981) on the effects of deterministic scheduling and Gutierrez and Kouvelis (1991) on the effects of Parkinson’s law, he does not mention that those papers have not provided any solution for the existing problems while Goldratt (1997) suggested to eliminate due dates in all cases in order to avoid Parkinson’s law and the student syndrome. Thirdly, Trietsch (2005a) questions the originality of using buffers as a method of protecting the project schedule, citing previous work by O’Brien (1965 cited in Trietsch 2005a). Herroelen and Leus (2001) cite another example from Clough et al., (2000) but they both neglect the point that different kinds of buffers (e.g. feeding and resource buffers) are deployed in CCPM and not only the project buffer which was used in the examples provided.

The novelty of the rule of no multitasking in CCPM is the fourth and last principle to be challenged by Trietsch (2005a). He refers to the issue of multitasking in past studies to show that proving its deficiencies is a simple deduction and Goldratt is not the first person to mention this. It seems that some aspects of Trietsch’s (2005a) and other authors’ (McKay and Morton, 1998; Elton and Roe, 1998) critiques regarding the novelty of CCPM are credible; however, as Steyn (2000) asserts, the aim in the analysis of CCPM should be to discover whether or not Goldratt has been successful in providing a package of pre-existing concepts which is able to benefit project management theory and practice. In another study, Lechler et al. (2005a) identify the differences of CPM/PERT and CCPM methods in a very precise manner and outline them in four well-organised tables. In contrast to Trietsch (2005a) who believes most of CCPM principles are not new to project management, Lechler et al., (2005a) conclude that CCPM is fundamentally different to traditional methods. In their viewpoint, CCPM is able to improve some behavioural aspects leading to continuous improvement of the project system.

Task Estimates and Durations

CCPM suggests estimating tasks to their 50% probability of on-time completion in order to exploit the constraint (critical chain) (Goldratt, 1997). This has become a very controversial issue within the CCPM debate. Raz et al., (2003) argue that there is not sufficient academic research to prove that estimators always include considerable safety times within activity

durations. They provide an example of a case study conducted by Hill et al., (2000) in a software development organisation which demonstrated that even in a company where many tasks are familiar to the estimators, although the majority of them (60%) overestimated activity durations, the overestimations were only 1% more than the actual duration and about 30% of tasks were completed later than estimated. They conclude from the case study that the estimators do not overestimate noticeably. However, a weakness of this judgment is lack of consideration of the CCPM rationale for 50% probability estimation, which is that these significant safety times which are added to the 50% probable finish date are not deployed efficiently because of student syndrome and Parkinson's Law (Goldratt, 1997; Leach, 1999; Steyn, 2000). Contrary to what Raz et al., (2003) deduce, the study of Hill et al., (2000) proves that the large safety times included in the task durations are not being used to deliver activities earlier and still a noticeable percentage of them are being completed late. In another study, Ribera et al. (2003) showed by means of a survey that about two third of respondents admitted that they embed safety times in their task estimates.

Raz et al. (2003) continue their critique by correctly asserting that not every employee considers the same amount of safety time and not every task contains the same amount of uncertainty. Herroelen and Leus (2001) raise the same issue in their paper. In addition, Nicholas (1990 cited in Steyn, 2000) states that there are many people who underestimate the time of their allocated tasks because of their high confidence in completing them on time. On the other hand, Umble and Umble (2000) assert that CCPM has the proper means for responding to this issue within its probabilistic principles. It advises estimators to consider a 50% probability for their tasks to be completed, thus it expects only half of the tasks to be completed on time and another half to be finished later than expected. With half of the tasks predicted to be delayed, CCPM includes a reasonable safety time for different types of estimations (overestimation and underestimation) and different levels of activity risks (Umble and Umble, 2000).

Raz et al. (2003) and Lechler et al. (2005a) also question whether or not employees of the organisation will agree to halve their estimated durations and not to add safety to their estimates in the future. While this is a possible phenomenon, the CCPM process includes: "do not allow inertia to become the constraint of the system" as its fifth step of continuous improvement process (Leach, 2005). Generally, a more important problem is the place of the considered safety times and not their length (Steyn, 2000). CCPM recommends separating the safety times from activities in order to prevent student syndrome and Parkinson's law from wasting those contingencies.

Rescheduling

Although CCPM proponents claim that the critical chain rarely changes during the project's execution, there is also some contradictory evidence regarding this issue. Herroelen and Leus (2004) believe that inevitable changes in the projected schedule (the CCPM schedule without showing buffers and gaps in the network) is in fact a type of project rescheduling that is being undertaken in CCPM and is remaining unacknowledged by its advocates. They also claim that this emphasis on rescheduling prohibition may be the reason for CCPM not being appreciated in projects such as new product development projects where reiteration of project stages necessitates rescheduling (although Sood (2002) provides contrary evidence to this by giving examples of a number of research-based organisations that adopted CCPM successfully). Lechler et al., (2005a) correctly mention that the critical chain might alter during the project

execution due to the difference in principles of determining the critical chain and the buffers. They state that while the critical chain is selected using both activity precedence and resource dependencies, the buffers are only based on the duration of their preceding chain of activities.

Furthermore, Hoel and Taylor (1999) and Herroelen and Leus (2001) show that the critical chain might change when, on some special occasions, a feeding buffer with a longer duration than the available slack and shortened activity times is added to a non-critical chain. As Herroelen and Leus (2001) continue, there are two solutions for this problem. The first one is to begin the whole schedule earlier in time in order to make the buffer insertion possible. The second one is to reschedule the entire project. Moreover, Cui et al. (2010) provide two methodologies to be considered after a change has occurred to the schedule. Piney (2000) also suggests cutting the feeding buffer in two segments and leaving one as a feeding buffer and moving the other part to the end of project and adding it to the project buffer.

On the other hand, Steyn (2000) states that appropriate management of buffers can guarantee the stability of the critical chain. Newbold (1998) also recommends project managers not to reschedule projects or reconsider the critical chain unless significant changes occur to buffer levels or resource timetables. However, it can also be beneficial to take the critical chain into account as the chain of activities that is able to alter the project duration during the monitoring function (a focusing tool) (Herroelen and Leus, 2005).

Buffer Sizing

CCPM separates the safety times from the median task time and aggregates them after each chain of activities under the name of project buffer after the critical chain and feeding buffer after each chain of non-critical activities (Leach, 2014). In order to shorten the project duration, these aggregated contingencies must be shorter than when they were calculated as part of the task durations. Goldratt (1997) simply suggests deducting 50% of the safety times based on the 50% probability of task estimations where at least half of them are expected to be completed on time. Raz et al. (2003), Lechler et al. (2005a) and Herroelen and Leus (2001) raise this issue of buffer sizing in their papers. Herroelen and Leus (2001) explain the problem by asserting that Goldratt's method of buffer sizing is linear and buffer sizes constantly increase as time increases. They have shown by their calculations that using the 50% buffer sizing method can lead to unnecessary long project durations. To answer those criticisms, there are also some sources that have provided more accurate methods for buffer sizing that will be discussed in the next section for improving studies.

Simple or Complicated Monitoring

Project monitoring in CCPM is conducted by measuring the level of feeding and project buffers' penetration during the project. Some authors have identified this as an advantage of CCPM because of its simplicity compared to traditional methods (Steyn, 2000; Leach, 1999). However, some others show that buffer consumption monitoring is a complicated function in large projects (Raz et al., 2003; Lechler et al., 2005a; Wilkens, 2000).

Resource Buffers

Resource buffers are the alarms that are triggered by the tasks approaching their start time on the critical chain. They inform the resource allocated to a specific critical task of the time the resource should be ready to begin working on that activity. Lechler et al., (2005a) assert that this is an alarm already used in the traditional methods. Raz et al., (2003) also add that using resource buffers causes a disorganised environment and does not enhance the previous method of exposing the project schedule to all project team members. Moreover, Herroelen and Leus (2001) mention the weakness of resource buffers to address the situation when two equal resources are able to perform a task.

In addition, Tukel and Rom (2006) mention a number of more practical problems with implementing resource buffers. Firstly, a resource might receive many alerts at the same time from the project manager if s/he has been allocated to several tasks in different projects. If this happens it may lead to higher confusion and anxiety and it is not clear whether the resource is allowed to stop working on a critical task and start another. Secondly, the project manager is not able to plan for the time and number of resource buffers and needs to wait for the project to be executed in order to decide whether s/he needs to create them. In this regard, Piney (2000) recommends using optimistic estimates of tasks' duration, as carried out in PERT, to identify the correct time when resources must be available. Tukel and Rom (2006) also believe that resource buffers have a number of benefits: delay is less likely when resource buffers are used to manage highly uncertain tasks and shorter project buffers are needed for project protection when using resource buffers.

Multitasking

CCPM does not allow multitasking in general. Clarke and Wheelwright (1993) suggest that the most efficient number of tasks that can be allocated to one resource is two which McCollum and Sherman (1991) confirmed by achieving the same outcomes in a study of a number of high technology companies. In addition, Herroelen and Leus (2001) claim that multitasking does not cause negative effects all the time and keeping employees under stress to complete a single task earlier can destroy morale. As Pinto (1999) asserts, this effect on morale is intensified in organisations that require fundamental cultural changes in order for their employees and top management to agree on full commitment to completing one task before proceeding to another.

Multi-Project Management

In contrast to traditional project management methods, CCPM contains clear instructions for multi-project management that have encountered some criticisms (Lechler et al., 2005a). Raz et al., (2003) state that the volatile environment of projects does not match CCPM techniques for multi-project management, since many resource contentions might occur and they might change during project execution. In response to this critique, Leach (2014, p.201) suggests selecting one of them as the Capacity Constrained Resource (CCR) based on criticality of a resource to the type of company (e.g. an engineer in an engineering company) or how difficult it is to elevate a resource. It is also claimed that the iterative nature of CCPM (5-step process) can ensure the consideration of other resources if the CCR changes in the process of project execution (Dass and Steyn, 2006).

In addition, research conducted by Cohen et al., (2004) showed that the CCPM method for managing multi-project environments is not the best and some other methods provide better results, although they only considered its performance in projects identical to aircraft maintenance projects. On the other hand, Rizzo (1999) advocates the use of CCPM techniques in a multi-project environment and claims that they provide project and top management with the essential “operational measurements” they need to manage risk and resource allocation in an organisation while maintaining control on all projects being undertaken.

Late-Start Scheduling

Smith-Daniels and Aquilano (1987) conducted research showing that using the late-start schedule leads to considerably shorter duration and better cash flow. Goldratt (1997) and Leach (1999) provide some benefits of starting tasks as late as possible (shorter duration with better cash-flow, less major change effects and better control over the project). Moreover, Newbold (1998) describes that late-start scheduling reduces the work-in-process. He also explains that reducing work-in-process can minimise the number of reworks because the less time the client has the less changes s/he imposes on the initial design.

On the other hand, work-in-process is not a significant factor in some types of projects, instead minimising the schedule is the first priority (Herroelen and Leus, 2001). In addition, Zwikael et al. (2006) mention some of the drawbacks of late-start scheduling to be the higher risk involved in finishing a project on time, less efficient resource utilisation, little justification for negotiating for more resources in a right-shift project and missing the opportunity of achieving a sense of unity in the project team because of later team assembly. However, they fail to support their claimed disadvantages with sufficient evidence. As another critique, Herroelen and Leus (2004) remind researchers that there are projects (e.g. new product development projects) that have no clear completion date and as a result their activities need to be scheduled as soon as possible. In general, it seems that selecting the early or late start schedule primarily depends on the priorities of every single project.

Improving Studies

This section attempts to answer the third research question of this study. Following the identification of CCPM weaknesses by critical studies, researchers started focusing on the improvement of different aspects of the method. Half of all 56 improving studies focused on improving the buffer sizing methods as a major issue in CCPM principles and the other half were written on a variety of subjects that will be discussed below. This section identifies improvements and helps to compare them with the previously discussed critiques of CCPM in order to locate the areas that still need further investigation in the future.

Task Duration Estimation Improvements

Following the critiques of the arbitrary task estimates in CCPM, Schuyler (2000) suggested using Monte Carlo simulations to identify more reliable task durations in projects. Others (Shou and Yeo, 2000; Rezaeie et al., 2009) related the duration estimate of each task to its level of uncertainty.

Buffer Sizing Improvements

After Goldratt (1997) recommended the 50% buffer sizing rule (placing half of the reduced duration of each path in the end of it as a time buffer), many other authors have attempted to create more scientific and effective rules. The Product Development Institute (1999) introduced the Root Square Error Method (RSEM) (Leach (2005) identifies this as Square Root of the Sum of the Squares (SSQ)). Newbold (1998) also provides a formula that encompasses the level of safety times considered for different tasks and therefore the uncertainty associated with them, using a lognormal distribution. Furthermore, Leach (2003b) considers possible biases included in buffer estimation that might lead to its underestimation. He defines bias as “anything that might invalidate pooling of variances of the individual tasks to size schedule or cost buffers” and introduces the Bias Plus Root Square Error Method (BPRSEM) in order to include those biases. BPRSEM is a combination of buffer sizing techniques for common cause variances and a safety time (about 10-25% of the buffer) added to the outcome of calculations because of the biases included in estimating task durations due to special cause variances (Leach, 2005).

In addition to the above, there are some other buffer sizing methods, namely High Confidence RSEM by Ashtiani et al., (2007), Adaptive Procedure With Resource Tightness and Adaptive Procedure With Density by Tukel et al., (2006), Improved RSEM (IRSE) by Xue-mei et al. (2010), Forecasting Error Approach by Caron and Mancini (2008), RSEM Based on Lognormal Distribution and Dependence Assumption Between Activities by Bie et al. (2012) and some other highly sophisticated approaches using computerised simulations (Tenera and Cruz Machado, 2007) and Fuzzy Logic (Shi and Gong, 2009; Min and Rongqui, 2008; Long and Ohsato, 2008).

Apart from the 50% rule, RSEM (based on normal and lognormal distributions) and BPRSEM methods, others have not been used in CCPM software products or implementation cases and not even widely mentioned in other academic investigations. However, based on positive results of validations mentioned in those papers, they can be considered as improvements in the way they take into account factors such as resource tightness, number of activities, number of dependencies, levels of risk and past experiences of the same project organisation that makes their produced buffer more reliable than the prevalent methods.

Project Monitoring Improvements

As mentioned above, the complexity of CCPM monitoring method has been a subject of discussion among researchers. In order to address this complexity, a number of studies have considered a simplified CCPM that does not include feeding buffers (Lechler et al., 2005b cited in Lechler et al., 2005a; Leach, 2003a). Leach (2003a) suggests a simplified CCPM that can eliminate the gaps sometimes created in CCPM schedules and make a simpler network for monitoring. Some others used earned value techniques to improve how CCPM monitors projects (Piney, 2000; Schuyler, 2000; Levine, 1999; Silber, 2002) which helped them to be able to predict the effect of delay in each task on its subsequent buffers, using the existing software products such as Microsoft Project.

Late-Start Scheduling Improvements

In accordance with late-start scheduling issues, there are a number of authors such as Ming and Wuliang (2009) and Peng and Xu (2012) who have introduced a new method of CCPM called Active CCPM. This new method deploys an early-start schedule for specific types of projects such as those in the IT industry.

Other Improvements

Improving studies also focused on aspects of CCPM that had not been criticised by critical studies before. One of them is to find an optimised scheduling algorithm for CCPM using the operations research methods (Peng et al., 2007; Long and Ohsato, 2008; Peng and Huang, 2013; Wuliang et al., 2013; Liu et al., 2013; Pawinski and Sapiecha, 2012; Wei-xin et al., 2013; Weixin et al. 2013). Their objectives have been to find an optimum solution for resource allocation, rescheduling, buffer insertion and project duration in CCPM. Another aspect is to improve CCPM reliability via combining it with the existing risk management techniques (Steyn, 2002; Mansoorzadeh and Yusof, 2011; Mansoorzadeh et al., 2014; Thipparate, 2014). One last aspect considered by improving studies has been identification of CCPM success factors by Repp and Wright (2013) and Simpson and Lynch (1999).

Empirical Studies

These studies constitute only 8% of total of studies under consideration of this paper; however, they play an important role in evaluating some of the core CCPM tools and techniques. Empirical papers have mostly used games, experiments, simulations and statistical analyses to investigate CCPM principles and, as explained under the following codes, the majority of them demonstrate better performance of CCPM compared to other methods.

Comparing CCPM and Traditional Project Management Methods

Budd and Cooper (2004, 2005) compared the time performance of the same project schedule with CPM/PERT and with CCPM techniques using both experimental analysis and simulations. In both cases CCPM performed considerably better in terms of projects' finish times. In another study, Huang et al. (2012) compared the time performance of PERT and CCPM schedules by means of simulations and concluded that: a) in a single project environment, CCPM performs slightly better than PERT in producing a shorter schedule b) in a multi-project environment, PERT performs slightly better in producing a shorter mean duration while CCPM is more stable and reliable during the project execution. Bhushan and Raghavan (2013) also compared CCPM and line of balance in construction projects and concluded that the line of balance provides a better time performance in such an environment. Another experimental study conducted by Yang (2007) observed that CCPM schedule performs better compared to the traditional CPM method in a construction environment. Moreover, one last study compares CPM and CCPM schedules by means of a simulation and achieved shorter project durations and higher chance of meeting project deadline with CCPM. Despite above results, it was found by Tian and Demeulemeester (2014) that the roadrunner mentality in CCPM cause inferior results in terms of stability and cost compared to the traditional railway mentality.

Validating the CCPM Reasons for Multi-Project Time Performance Failures

Huang et al. (2011) invited 210 project managers, resource managers and engineers to take part in a game designed for simulating a multi-project environment. They demonstrated that in contrast to the general belief (90% of more than 300 managers and engineers surveyed in their study) that multi-project attempts fail because of the high level of uncertainty, they mostly fail because of detrimental project planning and management practices addressed by Goldratt, such as multitasking, lack of understandable prioritisation of projects, wasting safety times and losing control.

Comparing CCPM Priority Rules and Some Other Alternatives

CCPM uses rates of buffer consumption for allocation of constrained resources to new projects in a multi-project environment. Cohen et al. (2004) compared this with other traditional priority rules for resource allocation such as the minimum slack and first come first served rules and concluded that the minimum slack rule performs slightly better than the CCPM buffer system in meeting the project deadline. In another study, Dass and Steyn (2006) showed by means of an experiment that there is no considerable difference between the performance of CCPM and minimum slack priority rules while CCPM produces shorter project duration.

Comparing Buffer Sizing and Insertion Methods

Geekie and Steyn (2008) examined the two most prevalent buffer sizing methods of the 50% rule and RSEM by means of simulations. They realised that while the former overestimates the buffer sizes, the later produces appropriate buffer sizes in the absence of bias. This can validate the importance of BPRSEM buffer sizing method introduced by Leach (2003b). Regarding the best place for inserting buffers in a CCPM schedule, Van de Vonder et al. (2005, 2006) showed that a better duration and schedule robustness trade off is achieved when buffers are located after each path, as CCPM suggests, instead of scattering them among the tasks as in traditional methods.

Case-Reporting Studies

A total of 20 studies (13%) on CCPM case studies or results were identified by this paper. This number excludes websites such as Realization.com or Goldratt.com that have reported on CCPM implementations (all reporting 100% success). Shortage of practical evidence has always been a reason for organisations not to adopt CCPM and these studies help to overcome this. The studies have been conducted in various industries, from construction and pharmaceutical industries to maintenance projects in the US Department of Defence shipyards. This variety shows that there is successful evidence for implementation of CCPM in all sorts of projects, from low to high uncertainty/complexity. Only one case of failure was reported in the construction industry that was attributed to late initiation of the transition programme while other cases have all been successful with an average reduction of 40% for project durations. Some other reported benefits of implementing CCPM were more productivity, more transparency, better communication and collaboration, better on time delivery rate, less multitasking, better control and monitoring, increased throughput and reduced work in progress in multi-project management. These studies were subcategorised as follows:

- *Engineering Projects Cases:* Sood (2003), Hunsberger (2012), Fenbert and Fleener (2002), Morais and Sbragia (2012), Hwang et al. (2009), Taylor and Rafai (2003), Phillis and Gumede (2011), Ribera and Grasas (2003), Best (2006) and Srinivasan et al. (2007).
- *Construction Projects Cases:* Sood (2003), Hunsberger (2012), Barber et al. (1999), Archibald et al. (2007), Kishira (2006), Stratton (2009) and Spanholtz and Stokes (2000).
- *Pharmaceutical Projects Cases:* Sood (2003), Hunsberger (2012), Marris (2011) and Sood (2002).
- *Maintenance Projects Cases:* Srinivasan et al. (2004), Bevilacqua et al. (2009) and Hunt (2004).

Exploiting Studies

TOC is claimed to be a holistic management philosophy and based on this it can be applied to any management environment, from personal life to most complex systems in manufacturing or project management. As a result of this, its principles, that also apply to CCPM, can be adapted to different environments. A number of authors (10) have used this capability and applied CCPM to sectors other than project scheduling. Those applications (with no codifying or subcategorising because of the low number of them) are: audit operations of an accounting firm (Yang, 2011), procurement and supply chain management in construction and other projects (Yeo and Ning, 2002, 2006; Wei and Ying, 2013; Trietsch, 2006), location-based management in construction projects (Buchmann-Slorup, 2013), determining the functionality of software products (Miranda, 2004), maritime disaster rescue operations (Yan et al., 2009), optimising the maintenance period of power plant electrical equipments (Dong et al., 2013) and reduction of costs in a manufacturing company (Taylor and Rafai, 2003).

Future research

Leach (2014) believes that CCPM is not yet the standard in industry; however, it has overcome obstacles of ignorance and rejection from the project management community. During the last 17 years, many suggestions have been made by researchers for improvement of initial CCPM tools and techniques with the aim of promoting CCPM in mainstream project management, but there are still a number of subjects that require researchers' attention; 21 of them were extracted from the 140 studies under scrutiny of this paper using their recommendations for future research and critiques developed within their contents and comparing them with the improvements already achieved in the improving studies. The aim is to answer the fourth and last research question of this study. The studies in the literature show that there is still need for more research on:

1. Severity of the schedule robustness issue in CCPM after insertion of buffers and during the execution of the project and providing solutions for it (Gray et al., 2000; Lechler et al., 2005a; Koskela et al., 2010). Both case studies and simulations can investigate this.
2. Safe resource loading and availability rates (sizing an organisation's resource pool) in order to meet the scheduled deadline especially in multi-project management and after eliminating task due dates (Tukel and Rom, 2006; Patrick, 1999a, 1999b; Wilkens, 2000; Rizzo, 1999; Trietsch, 2005a).

3. Differences between project durations produced by optimised and heuristic scheduling algorithms (Tukel and Rom, 2006). This helps to find out how much time and resources are wasted in heuristic scheduling rules being used in existing software products and whether they are negligible compared to the existing optimised algorithms mentioned earlier.
4. Advantages, disadvantages and feasibility of using EVM for time and cost control purposes in a CCPM environment (Piney, 2000, Schuyler, 2000; Levine, 1999; Silber, 2002).
5. The appropriate level of multitasking in CCPM projects as it has always been a controversial subject in CCPM because of its need for severe cultural changes in an organisation (Herroelen and Leus, 2001, 2004; Pinto, 1999).
6. CCPM performance (using its software packages) in determining the critical chain, keeping it stable throughout the project, identifying CCRs and staggering projects in volatile projects such as product development projects (Herroelen and Leus, 2004; Raz et al., 2003).
7. Cultural and organisational barriers to the implementation of CCPM as it has always been mentioned as a major obstacle to CCPM adoption by new organisations (Pinto, 1999).
8. Financial aspects of managing projects, such as budgeting and cost control, in CCPM (Raz et al., 2003; Goldratt, 1999). Only one paper (Steyn, 2002) has focused on lack of rules for cost management in CCPM.
9. Effects of delays in completion of non-critical tasks on the project duration when they require same resources used to undertake critical tasks (Lechler et al., 2005a).
10. Sizing drum and capacity buffers in multi-project environments (Wilkens, 2000; Rizzo, 1999; Lechler et al., 2005a).
11. The best sequence for inserting buffers: feeding or project buffers (Herroelen and Leus, 2000).
12. Effects of non-project work distractions on the level of multitasking, dependency of activities on each other and project duration (Leach, 2003b).
13. Benefits of using the Criticality Index concept for selection of the critical chain using Monte Carlo simulation rather than doing it arbitrarily (Hoel and Taylor, 1999; Schuyler, 2000).
14. Possible applications of the queuing theory in sizing buffers and resource pools in organisations by considering each resource as a server and each task as a customer (Xiao-Ping and Pan, 2011).
15. The probable negative effects of considering the wrong critical chain as the initial constraint of the project or keeping focus on a chain that is no more the real constraint (Herroelen and Leus, 2001).
16. Conflicts between organisations' standard cost accounting procedures and CCPM principles that prevent them from adopting CCPM. Role of EVM and cost buffers in finding a solution for those conflicts (Piney, 2000, Schuyler, 2000; Levine, 1999; Silber, 2002).
17. Modelling project tasks' variability in CCPM simulation studies and considering their dependencies on each other (e.g. same risks) and relative dispersion values (Shou and Yeo, 2000; Herroelen and Leus, 2001; Lechler et al., 2005a; Bie et al., 2012; Leach, 2003b).
18. Effects of implementing a roadrunner (relay racer) mentality on availability of required resources for subsequent tasks (Tian and Demeulemeester, 2014).

19. The relationship between CCPM principles and risk management techniques for mitigating identified risks (Patrick, 2001).
20. Implications of using PERT probabilistic methods in estimating task durations in CCPM (Piney, 2000).
21. The application of a location-based method in CCPM in order to consider the location of work in the construction industry (Koskela et al., 2010).

Conclusions

This paper used the “hierarchical coding” method to critically review the literature of CCPM published in journals and conference proceedings since its introduction in 1997. 140 papers were analysed and it was shown that there is still ongoing research being conducted on the method and although with a slower pace, CCPM studies are still being published (first research question). In response to the second question, six categories of approaches towards CCPM (introductory, critical, improving, empirical, case-reporting and exploiting) were identified and their contributions discussed, one of them being improving studies. The improvements brought by these studies were then discussed and compared to other studies in order to find what shortcomings have been addressed and what aspects of CCPM still remain open to more investigations (third research question). Finally, to answer the fourth question and as a major contribution of this paper, these shortcomings were used to produce a list of CCPM areas to be developed in the future. Should these areas be more investigated, CCPM is probably able to become a more widely used method across all industries which use project management.

In general, this paper showed that CCPM has been on a long journey since 1997, from studies on introduction of the new method, evaluating it and finally improving its techniques. Following the “hierarchical coding” method, it can be concluded that the theme of research has been more introductory and critical during the first decade after the introduction of CCPM (Figure 4) while this later changed to an improving theme within the research on CCPM with more improving studies being published than others. In parallel, there have always been authors who reported on CCPM implementation cases (case-reporting), deployed its capabilities in other environments (exploiting) and verified its principles (empirical). With respect to the future, it seems that the focus of researchers needs to be on improving the method and reporting on its implementation cases in order to address the points raised within the list of the 21 identified areas of CCPM shortcomings.

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