CRITICAL CHAIN PROJECT MANAGEMENT

SEMINAR IN INDUSTRIAL ENGINEERING

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INTRODUCTION

This project aims to extract and display the most important concepts about Critical Chain Project Management (CCPM).

Eliyahu M. Goldratt's novel "Critical Chain" expresses the main ideas about a methodology that was a success and many researches were carried out after his book.

In this recompilation, it will be analyzed many papers that have been written about CCPM and their different approaches. We must understand that projects are activities that, to a greater or lesser scale, affect all companies. We also know that activities do not remain static over time but they are changing.

Firstly, I will provide an overview of each book and research including goals, motivations, analysis and contributions to the science and the world of the industrial engineering in particular.

Secondly, I will give my opinion about each book and research and the connection with the next research/book.

Lastly but not least, I will give a general overview and summarize of all the papers, including the citation’s rate of each one. Moreover, it will be mentioned some software and smartphone applications regarding to CCPM.

Before starting we have to answer two main questions:

1) What is a Project?

It can be defined as a set of activities to achieve a goal with a specific start date and end date.

2) What are the most common projects problems?

The vast majority of the projects tend to have the following problems:

A) Finishing out of date

B) The budget is exceeded.

C) Modification of activities due to A and B

PAPERS ORDER CRITERIA

1) Background of CCPM
2) CCPM concepts and fundamentals
3) Project performance using CCPM
4) CCPM applied to Project Management
5) Critical view and comparison to other methodologies
6) Some examples using CCPM
7) Multi projects and comparative with different methodologies
8) Parkinson’s Law
9) Buffer sizing

LIST OF PAPERS AND BOOKS

#	RESEARCH	JOURNAL/EDITORIAL	AUTHOR	YEAR
1	The goal: a process of ongoing improvement	(Book) The North River Press Publishing Corporation	EM Goldratt, J Cox, D Whitford	1984
2	Drum-buffer-rope shop floor control	Production and Inventory Management Journal	E Schragenheim, B Ronen	1990
3	Theory of constraints	(Book) The North River Press Publishing Corporation	EM Goldratt	1990
4	Critical Chain	(Book) The North River Press Publishing Corporation	E.M. Goldratt	1997
5	Critical chain project management improves project performance	Project Management Journal	LP Leach	1999
6	Critical chain: the theory of constraints applied to project management	International Journal of Project Management	GK Rand	2000
7	An investigation into the fundamentals of critical chain project scheduling	International Journal of Project Management	H Steyn	2001
8	A critical look at critical chain project management	Project Management Journal	T Raz, R Barnes, D Dvir	2004
9	Critical chain: a new project management paradigm or old wine in new bottles?	Engineering Management Journal	TG Lechler, B Ronen, EA Stohr	2005

10	Project management applications of the theory of constraints beyond critical chain scheduling	International Journal of Project Management	H Steyn	2002
11	Multi-project scheduling and control: A process-based comparative study of the critical chain methodology and some alternatives	Project Management Journal	I Cohen, A Mandelbaum, A Shtub	2004
12	A new heuristic for resource-constrained project scheduling in stochastic networks using critical chain concept	European Journal of Operational Research	M Rabbani, SMTF Ghomi, F Jolai, NS Lahiji -	2007
13	Parkinson's law and its implications for project management	Management Science	Gutierrez, G. J., & Kouvelis, P.	1991
14	Integrating supply chain and critical chain concepts in engineer-procure-construct (EPC) projects	International Journal of Project Management	KT Yeo, JH Ning	2002
15	Critical chain project management theory and practice	Journal of Project Management and Systems Engineering	R Stratton	2009
16	On the merits and pitfalls of critical chain scheduling	Journal of operations management	W Herroelen, R Leus	2001
17	A new approach for buffer sizing in critical chain scheduling	Industrial Engineering and Engineering Management	Ashtiani, B., Jalali, G. R., Aryanezhad, M. B., & Makui, A	2007

1. The goal: a process of ongoing improvement

(Book) The North River Press Publishing Corporation - EM Goldratt, J Cox, D Whitford - 1984

GOAL

- Bottleneck analysis.

MOTIVATION

- Nobody had focus the bottleneck problem from a didactic point of view.

ANALYSIS

Alex Rogo, the main character of this novel is a production manager in a plant owned by UniCo Manufacturing. All the activities in his plant are always behind schedule and this problem would cause the bankrupt if things will not change. Bill Peach, one of the directors of the company advices Alex to improve the situation or the company would close. Rogo has three months to turn operations from being delayed and unprofitable to being successful. Jonah, an expert physicist, (Goldratt represents himself) gives Rogo some pieces of advice to solve the company's problems. In parallel, a second story line describes Rogo's marital life and his function as father.

Rogo discovers that bottlenecks' identification allows not only eliminate them but also allows control and measure the material flow.

Gradually, the books makes the reader to move through a series of phases to establish the principles for the discussion. The writer tries to explain it from the point of view of the reader, it means using a little bit of project management background but pretending to be an ignorant about the solution of the managing problems in order the reader to discover at the same rhythm that the writer the solutions.

CONTRIBUTIONS

- Role of bottlenecks.
- Any system has a constraint that limits its output. This will be, then, the lemma of Critical Chain.
- The goal: “to make money by increasing net profit, while simultaneously increasing return on investment, and simultaneously increasing cash flow”.
- This book is the precedent to Critical Chain Project Management.

PERSONAL OPINION

It is an excellent book, very gripping and clear. I had to read it during my BSc in Industrial Engineering in Argentina (it was part of the Project Management course). It was very useful to understand the bottleneck problem. This book is the first of many others written by Goldratt and because of this one, he will become one of the most important referents of Project Management.

CONNECTION WITH NEXT PAPER

This book is the base of the many books and papers that came up afterward. The next research was the first one after this book in using many concepts and, also, specific words such “drum” (Alex Rogo in the book associates the main constraint to a drum that determines the pace of all the group of boy scouts during his experience with kids than later he will apply for solving some problems in his company)

2. Drum-buffer-rope shop floor control

Production and Inventory Management Journal - E Schragenheim, B Ronen - 1990

GOALS

- DBR pretends to be a new methodology.

MOTIVATION

- Based on the concepts taught by Goldratt in The Goal, they proposed a new methodology for dealing with Project Management Scheduling.
- Schragenheim et al consider that to achieve shorter project lead times, companies should focus on improving the flow of projects using similar logic to that of lean manufacturing and, of course, using Drum-Buffer-Rope

ANALYSIS

Scheduling in Drum-Buffer-Rope:

Step (a) Schedule your constraints

Step (b) Determine the buffer sizes

Step (c) All the materials should be subordinated to steps (a) and (b)

16 discrete runs were performed using these steps.

CONTRIBUTIONS

- Drum = Main constraint resource.
- Buffer = protection time.
- Rope = mechanism to force all the part of the chain to work up exclusively for to the pace dictated by the drum and no more.
- New methodology.

PERSONAL OPINION

This paper is very short but has a very easy and useful method to deal with scheduling in Project Management. Of course, it is too much simple and has not neither mathematical analysis nor justification.

CONNECTION WITH NEXT PAPER

This paper was very useful for Goldratt to understand that The Goal was an excellent book where methodologies could arise from it. For this reason, he will write the next book.

3. Theory of Constraints

(Book) The North River Press Publishing Corporation - EM Goldratt -1990

GOALS

- How to schedule a single project to reduce project duration and improve project control?

MOTIVATION

- The main constraint is like the weakest link of a chain.

ANALYSIS

The bottleneck in production planning terms is the constraint of the system. If the constraint is a machine, for instance, must be achieved the maximum possible efficiency of this machine. It means that all the efforts should be focus on the machine and, for instance, running the machine during the lunch hour, reducing the quantity of changeovers, avoiding stops and all the activities necessaries to guarantee that the machine is always working.

CONTRIBUTIONS

- TOC suggest relocating safety times in strategy position (then it will called Project Buffer and Feeding Buffer) in contrast with PERT that deals with uncertainty without taking into account if the activities are part of the CC or not.
- 5 steps of TOC approach:

1. Identify the constraints in the system

2. Exploit them
3. Everything should be subordinate to the above decision
4. Elevate the constraints of the system.
5. If a constraint has been broken in the previous stems, go back to step 1

PERSONAL OPINION

TOC has resulted a very useful tool to minimize inventory, service time and to maximize production and optimization of the process. Nonetheless, has some shortages such as the statistic approach since it does not take into account too much the uncertainty. It does not take into account, neither, that some constraints are external, not always internal. Because of this, in the real world these assumptions bring inaccuracy in scheduling.

CONNECTION WITH NEXT PAPER

Goldratt will write Critical Chain based on Theory of Constraints.

4. Critical Chain

(Book) The North River Press Publishing Corporation - E.M. Goldratt - 1997

GOALS

- New Project Management Methodology.

MOTIVATION

- At this time, existing methodologies were not good enough to deal with all the problems derived from the industry. Goldratt proposes a new Project Management methodology to deal with scheduling and to maximize benefits by reducing activity durations.

- CCPM introduces the concept of project buffer, feeding buffer and resource buffer. Buffer's goal is to administrate units of resources and time in order to "take care" of the CC (the longest chain of dependent steps that determines the time it will take to finish the Project), specially of the bottlenecks to avoid any delay since it is the minimum time that it will take the task to be completed.

ANALYSIS

It is now almost 19 years since Eliyahu Goldratt launched onto the market the first publication on Critical Chain. From 1997 to this day many research, simulators and implementations of this methodology have been rapidly developed.

Project buffer is inserted at the end of the project network, between the last job and the completion date. Although any delays on the longest chain will consume some units of this buffer, the completion date will stay unchanged and, consequently, the throughput time (the time span from its start-time until its finishing time) of the project will stay protected. The project buffer, according to the experts that later on this research we will analyze, should be half the size of the safety time taken out.

To protect against delays on paths of task feeding into the longest chain and preventing this impact into the project by delaying a subsequent tasks on the CC, it is very common adding feeding buffers between the last task on a feeding path and the CC. Feeding buffer is recommended to be half the size of the safety time taken out of the feeding path.

Since CCPM is a method of planning and managing projects that emphasizes the resources required to execute project tasks, resource buffer may be set alongside of the CC to ensure that there will not be any moment in which we will not be able to have people and skills available to work in the CC tasks as soon as we needed. For this reason, we should insure the resource has at least a 50% of chances of finishing the specific duty on time, adding a safety time called resource buffer.

Goldratt understands that educational system cannot continue as always and should change to better accommodate itself to the modern life and quickly changing world of business, especially regarding to projects

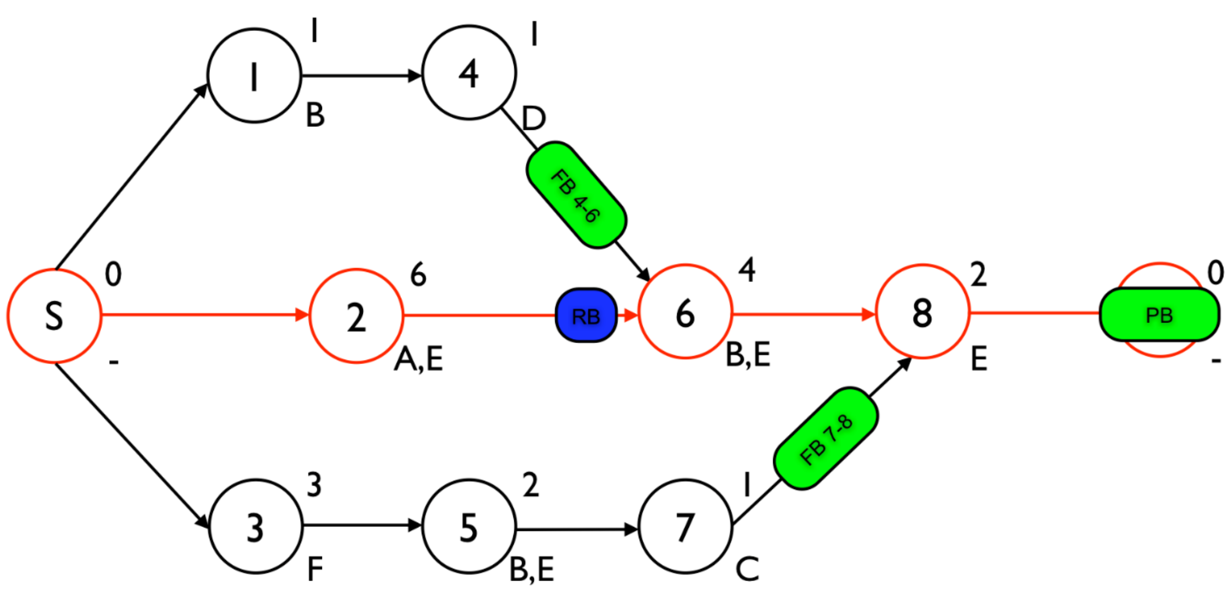
It provides a primer on the TOC and then an implementation in a steel mill to give the reader an example of TOC

For a single project, Goldratt defines the CC as the constraint. CC is the path that determines project duration

Goldratt demonstrates the application of TOC and then he proposes using Project Buffer for protecting the critical chain and also Feeding Buffers for avoiding the non-critical chain becoming the main constraint of the system.

CONTRIBUTIONS

- Managers should “think global and not local”.
- Main ideas about a methodology that was a success and many researches were carried out after his book.
- CCPM is the most popular project management technique for many multi project organizations
- Non-critical tasks should start ALAP but protected with feeding buffers to prevent any delay that make them part of the CC



PERSONAL OPINION

It is proved that this methodology is one of the most important methodologies in Project Management. At the end of this document, I will cite how much it is used in the academic world.

Shortcoming: lack of mathematical analysis, especially when he suggests using of 50% in buffer sizing.

CONNECTION WITH NEXT PAPER

Many researchers and writers decided to deepen in this methodology. One of the first one was Leach in 1999 when he studies it from a critical point of view but discovering how much useful is this approach.

5. Critical chain project management improves project performance

Project Management Journal - LP Leach - 1999

GOALS

- Theory and practice of CCPM.
- Difference with CPM.

MOTIVATION

- Application of the TOC philosophy to both single and multiple projects

ANALYSIS

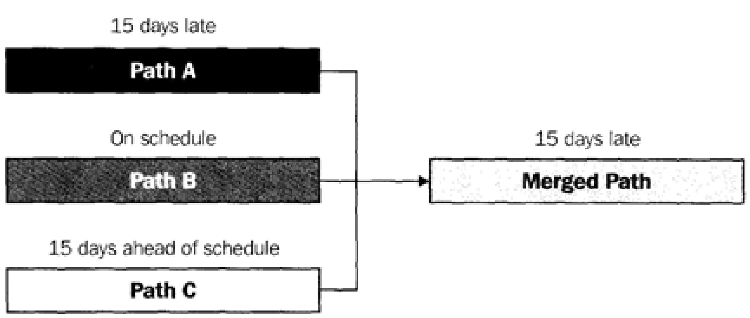
Harris Semiconductor (revenue of $2 per day, saved millions finishing in 14 month instead of 30), Israeli Aircraft Industry (maintain jumbo jets takes two weeks instead of three months), Lucent Technology (now Alcatel, plan reductions in excess of 25%)

Examination of milestone performance in an over 15.000 activities project: 80% activities finishing exactly on the original planned duration, just 1 o 2 activities earlier and almost 20% later (some too much later)

Use of the PMBOK Guide, a guide to Project Management Body of Knowledge.

CONTRIBUTIONS

- The importance of Buffers to achieve earliest project completion.
- Applications demonstrate effectiveness.
- List of the essential changes implemented by CCPM.
- List of undesired effects (multitasking, loss of focus, project delay caused by activity path merge).



PERSONAL OPINION

This paper shows us that, in fact, CCPM is very beneficial for scheduling. The three examples are very useful for understanding it. Nevertheless, this paper is very optimist with CCPM but does not take into account the mathematical approach of buffers.

CONNECTION WITH NEXT PAPER

Leach was not the only one interested in this methodology: Rand also investigated it deeply along with TOC.

6. Critical chain: the theory of constraints applied to project management

International Journal of Project Management - GK Rand - 2000

GOALS

- Close study of the Theory of Constraints.
- Application of the TOC philosophy to a single project.
- Close study of buffers.

MOTIVATION

- Why is TOC approach needed?

ANALYSIS

Rand studied deeply the work of Goldratt, especially the Theory of Constraints, and he summarizes this theory in five simple steps for implementation:

1. Identify the constraints in the system. There is always constraints. The system's constraint is that part of the system that constrains the objective of the system.

2. Once constraints were identified, decide how to exploit them

3. Everything should be subordinate to the above decision

4. Elevate the constraints of the system.

5. If a constraint has been broken in the previous stems, go back to step 1

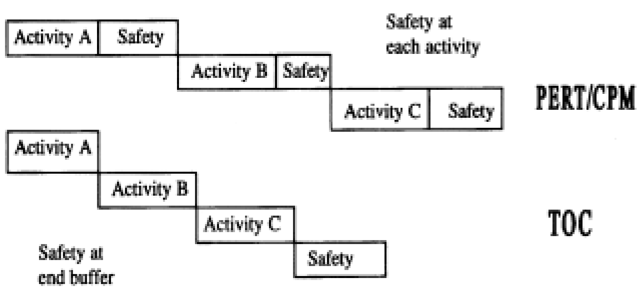
The bottleneck in production planning terms is the constraint of the system. If the constraint is a machine, for instance, must be achieved the maximum possible efficiency of this machine. It means that all the efforts should be focus on the machine and, for instance, running the machine during the lunch hour, reducing the quantity of changeovers, avoiding stops and all the activities necessaries to guarantee that the machine is always working.

According to Step 2, if there is another constraint we should treat it as well, but if not and this is the only one, then there is no point running other machines at a higher production rate because just the bottleneck determines the production rhythm.

Every other planning decision such as resource allocation needs to be subordinated to the necessities required by the bottleneck machine to keep it running (Step 3).

The system's constraint may need to be `elevated' to improve the objective. For instance, the bottleneck machine may be run during an additional shift to increase its output. The goal here is to elevate the capacity of the machine to improve its production rate and reduce the cycle time (Step 4). There is just one difference between Step 2 and 4: the amount of money required to improve the process (throughput, money and effort).

Sometimes, the application of Step 4 may change the bottleneck since the CC could become another machine. When increasing capacity, the original bottleneck may no longer the main constrain of the system. In this case, it is necessary to identify the new bottleneck and repeat the process again (Step 5).



CONTRIBUTIONS

- We need Critical chain to solve some chronic problems that existing methods, software and approaches have not been able to eliminate.
- Difference between PERT and TOC.
- Resource buffer, a warning system or reminders to assure the resources preparation when it is due time to work on a critical task.

PERSONAL OPINION

It is the best analysis of CCPM, but of course that took much background from Leach.

CONNECTION WITH NEXT PAPERS

Leach, Rand and Steyn were the first three researchers that understood the transcendence of this methodology and decided go deeper and deeper in the analysis of CCPM.

7. An investigation into the fundamentals of critical chain project scheduling

International Journal of Project Management - H Steyn - 2001

GOALS

- Investigate the assumptions and principles of TOC approach.
- Extensive review of the literature on TOC's application.

MOTIVATION

- Does TOC have enough potential to contribute meaningfully to PM practices?
- Investigate if the TOC philosophy to project time management reduces project duration for a single project
- A breakthrough or nothing new?

ANALYSIS

First of all, Steyn carries out deeply review of the literature on the TOC's application

Duncan's claim: TOC borrows main concepts from Forrester (1950) and from statistical process control before from World War II. TOC does not present new ideas

Drucker claims that TOC is not a new knowledge but new technology

Elton and Roe think that TOC is good dealing with single projects but it does not explain how to deal with multi projects. TOC has not yet found significant application in the field of project selection

Rand, Barber and Patrick describe the application of TOC to a single project

Leach and Newbold describe the application of TOC to multiple projects

CONSTRIBUTIONS

- TOC borrows main concepts from Forrester (1950) and from statistical process control before World War II.
- Because of the effect of aggregation, the buffer project is smaller than the sum of the reserves of each activity.
- Multi-tasking or jumping between projects may produce a negative effect in activity time.
- TOC is good dealing with single projects but it does not explain how to deal with multi projects.

PERSONAL OPINION

Multi-tasking was almost not taken into account until this time. This is the main challenge. The rest of the analysis is very similar to his predecessor, Rand.

CONNECTION WITH NEXT PAPER

In Israel, native country of Eliyahu Goldratt, Raz et al began to be very interested in this methodology and the dared to criticize it.

8. A critical look at critical chain project management

Project Management Journal - T Raz, R Barnes, D Dvir - 2004

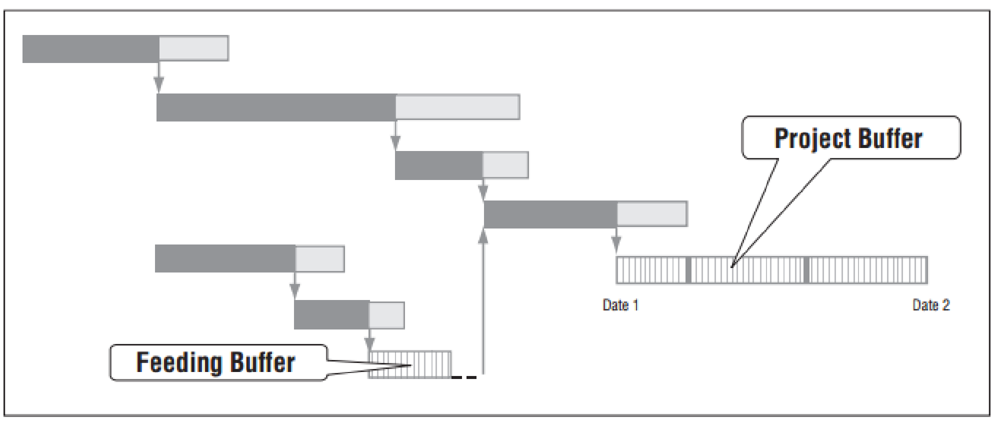
GOALS

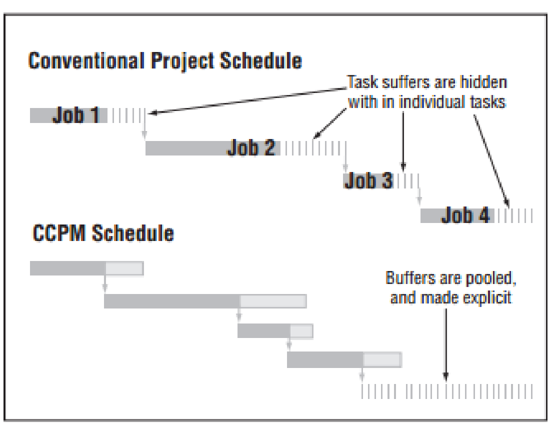
- Difference between CC and CP at a conceptual level.

MOTIVATION

- As Maylor (2000) and McKay and Morton (1998), they argue that it consists of known concepts presented in a different way. Later, Lechler et al demonstrates that it is not true. Is it something new or the same with different approach?

ANALYSIS





They used the general case of a Project Network to understand the duration of each activity. They also searched about companies using CCPM in scheduling.

CONSTRIBUTIONS

- TOC and Buffers are not necessarily new elements (Raz studied the impact of resource availability in 1996).
- CCPM is based on the premise that the main factor affecting the project time is the uncertainty in activity duration.
- There is no (by 2004) scientific evidence of the improvement in organizations by using CCPM.
- Very clear graphs about CCPM approach:

PERSONAL OPINION

The analysis is very similar to the Steyn's research. Nevertheless, Raz is more suspicious regarding to the successful of this theory since there is no real evidence of the improving in companies by using CCPM.

CONNECTION WITH NEXT PAPER

One year after this paper, many researchers started to distrust CCPM. Next paper is one of the main important researches distrusting CCPM.

9. Critical chain: a new project management paradigm or old wine in new bottles?

Engineering Management Journal - TG Lechler, B Ronen, EA Stohr - 2005

GOALS

- Analyze CC approach.
- Difference between CC and CP in two levels: philosophical and operational.

MOTIVATION

- Raz informed that there is no (by 2004) scientific evidence of the improvement in organizations by using CCPM.

ANALYSIS

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

Critical Path	Critical Chain
• Minimize project duration	• Maximize systems throughput.
• Performance of individual projects	• Performance of multiple project system constraint resource • Reduce WIP
• Not explicitly addressed	• Introduce drum and capacity buffers

• Maximize resource utilization of all resources • Multitasking not explicitly addressed	• Maximize resource utilization of constraint resources • Do not allow multitasking
• Several project prioritization rules	• Stagger projects along the systems constraint using drum and capacity buffers • Prioritize projects • Resolve resource conflicts on the systems level
• Not explicitly addressed	• Avoid multitasking

CONSTRIBUTIONS

- The main difference between CC and CP is that CC applies TOC.
- Philosophically, the goal of CC is not only minimize project duration in single projects but also maximize project throughput in multi-project environments.
- Differences between CP and CC Planning at Single and Multi-project.

PERSONAL OPINION

They made a detailed analysis of the difference between CP and CCPM and a philosophical analysis. No useful information about real experience.

CONNECTION WITH NEXT PAPER

All the papers have been researched about CP, CCPM and TOC. Five years after Critical Chain (the book), Steyn studies CCPM along with its risk management.

10. Project management applications of the theory of constraints beyond critical chain scheduling

International Journal of Project Management - H Steyn - 2002

GOALS

- Why TOC approach was, in the beginning, applied only to project scheduling?
- How to manage resources shared by multi projects?
- When a particular resource is overloaded, the organization cannot carry out many projects at the same time. How to solve it?

MOTIVATION

- Up to 90% (by value) of all projects are multi project (JR Turner).

ANALYSIS

Developing a risk management model for systematic risk reduction

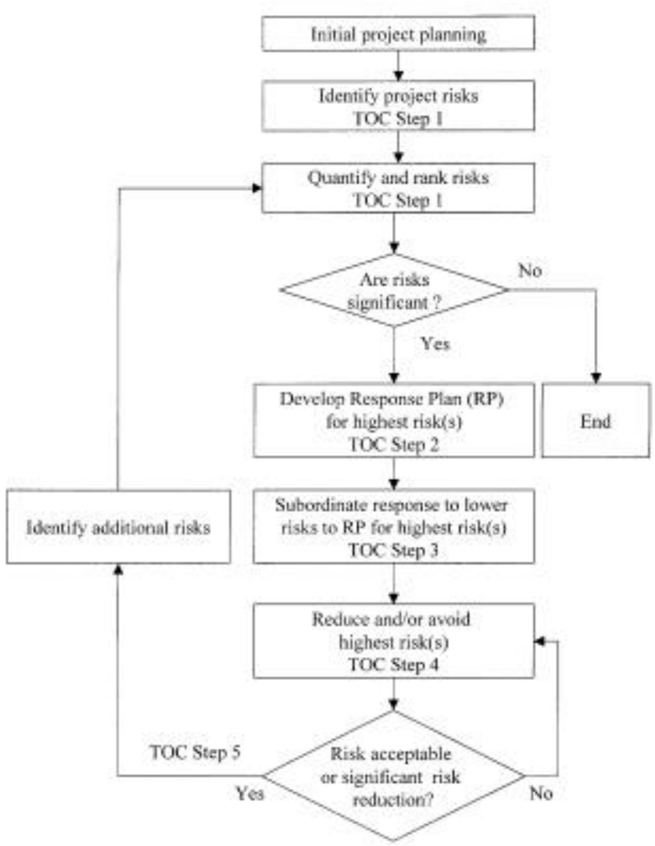


Fig. 2. Proposed risk management model for systematic risk reduction.

Maximization of the number of projects that a company can handle at the same time

CONSTRIBUTIONS

- TOC approach may also be applied to areas such as project cost management and project risk management.
- On a regular basis, concurrent projects depend on a pool of shared resources in a multi project environment.
- TOC has been extended in order to know how to allocate resources in multi projects that share common resources.
- As Newbold (1998), Steyn considers CC as the most important breakthrough for PM since the introduction of CPM.

PERSONAL OPINION

It was the first study that did focus on TOC in multi-project. Shortage: how to do project selection? TOC has not yet found significant application in this field

CONNECTION WITH NEXT PAPER

Steyn developed a great analysis for multi projects but we do not have conclusions about its effectiveness. CCPM is not the unique way to manage a project. What's more, there is no studies comparing CCPM with other methodologies in multi-project.

11. Multi-project scheduling and control: A process-based comparative study of the critical chain methodology and some alternatives

Project Management Journal - I Cohen, A Mandelbaum, A Shtub - 2004

GOALS

- Since many multi-project organizations have chosen CCPM for planning, scheduling, and control their projects, Cohen et al decided to study the performance of CCPM in a multi-project environment in comparison with the next methodologies:

- 1) Open controls: No Control, CCPM and MinSLK

- a) No Control: a system with FCFS (first come first served) queues priority rules
- b) CCPM
- c) MinSLK: highest priority in queue to a Minimum Slack Activity (slack-time is defined as the difference between the late start time and early start time). Each time an activity is completed, there is a reevaluation of the critical path and an updating of the slack times for the rest of the activities
- 2) Closed and semi-closed: ConPIP and QSC

- a) Constant Number of Projects in Process (ConPIP). New projects starts based on a predetermined quantity of projects in process (NPIP). Arriving project starts immediately its process if the number of projects concurrently in process within the system is below NPIP; otherwise, it waits until it can be processed in an external queue.
- b) Queue Size Control (QSC): this methodology allows a predetermined maximal number of activities. An arriving project is either allowed to be processed (if the length of the bottleneck's resource queue is below this maximal number) or discarded (if the length of the bottleneck's resource queue is over this maximal number).

MOTIVATION

- CCPM is not the unique way to manage a project

ANALYSIS

Considering a set of scare resources in a random environment of multiple concurrent projects, which at the same time are unique in that their activity durations and resource requirements differ and non-unique in that they share some preceding activities, Cohen et al analyzed analytically and numerally, the performance of the different approaches of PM

Always, each activity is either receiving service from a resource, queuing up for access to a resource, or waiting to join a previous activity

There are two considerations of broad significance to PM demonstrated by Cohen et al:

1) The trade-off between resource utilization and project throughput: according as resources utilization become higher, the project's throughput gets longer.

2) Some simple management methodologies, requiring low implementation costs and at the same time achieve a better performance compared to the CCPM. They claim it is because of the costs that organizational changes and CCPM implementation involves (mainly training costs for both management and workers).

In this paper, Cohen et al numerate the steps for carrying out a single and a multi project planning, scheduling and control

Step 1: Reduce as much as possible activity durations by eliminating safety margins, it means without adding extra time to any task.

Step S2: Identify the CC. It is the longest chain of dependent steps that determines the time it will take to finish the Project.

Step S3: Create a project buffer at the end of the project network, between the last job and the completion date.

Step S4: Create feeding buffers between the last task on a feeding path and the CC.

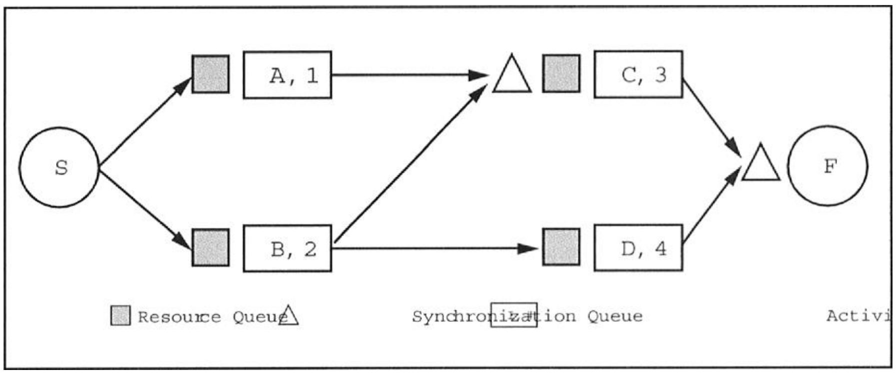
Step S5: Control.

Step M1: Although it is a multi-project, treat each project as a single project.

Step M2: Ordering projects according to the bottleneck resource.

Step M3: Create a capacity buffer (we set its base-case size at 50% of the duration of the bottleneck activity).

Step M4: Control. As with single projects, scheduling control of multi-projects is buffer-based.



This figure represents a simple multi project system which has four resource types (1, 2, 3 and 4), which process projects of a single type. A, B, C and D are de activities of each project: Type 1 resources process type A activities, type 2 resources process type B, type 3 resources process type C and type 4 resources process type D.

As usual, start and finish activities are simply milestones: they have neither a duration nor a resource requirement.

System characteristics:

	Resource Type	Number of Resources	Time Distribution
Inter-arrival			Exp(1/3.25)
Activity A	1	3	Exp(1/6)
Activity B	2	2	Exp(1/5)
Activity C	3	3	Exp(1/4)
Activity D	4	1	Exp(1/3)

We can appreciate that the bottleneck resource is resource 4. A single type 4 resource is used to activity D (utilization level: 3/3.25 = 92% in steady state).

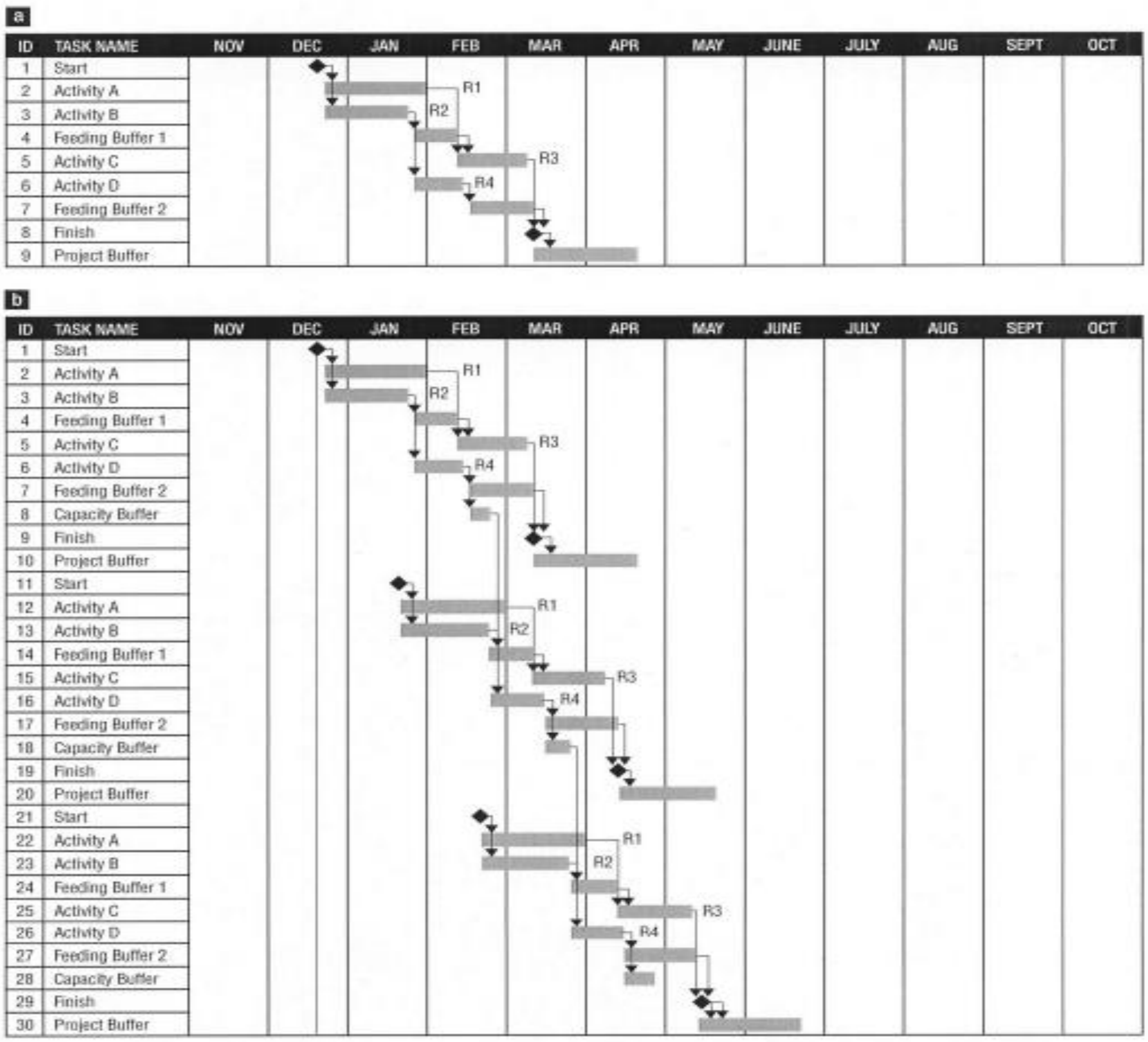


Figure 2. Critical Chain representation of a single project (a) and a corresponding multi-project system (b). For concreteness, one time unit is a week. The critical chain consists of Activity A and Activity C. Feeding buffers are added at the end of non-critical chains: the non-critical chain that includes Activity B (Feeding Buffer 1) and one that includes activities B and D (Feeding Buffer 2). At the end of the critical chain we add a project buffer. Capacity buffers decouple successive projects: such a buffer is placed after an activity performed by Resource 4 (bottleneck resource) in one project and this activity in the following project

The experimental was written in Visual Basic and replicated 50 times in order to compare system performance under CC with system performance under other methodologies. It was analyzed the following performance measures:

- mean project duration
- standard deviation
- throughput rate (how many projects were completed per unit of time)

CONSTRIBUTIONS

- Sometimes CCPM is not enough to prevent projects' lateness, but there are some other alternatives that provide similar and even much better performance than CCPM.
- Although CCPM is the most popular project management technique for many multi project organizations and although feeding, project and capacity buffers are added for dealing with stochastic variability, some other methodologies such as QSC, ConPIP, and MinSLK can give similar and sometimes better performance. In higher throughput rates it is recommended to work with QSC instead of CCPM.
- The most important trade-off that an organization's management should consider is that between resource utilization and project throughput time. Then we can ask whether to work at high traffic intensity levels that gives us a long throughput times or at low traffic intensity to gain lower throughput times and lower standard deviation.
- Further research: more robust scheduling and control mechanisms for multi-project stochastic environments.

λ	Instance	No Control	CC	MinSLK	QSC(6)	QSC(3)	ConPIP
0.31	$\bar{X}$	51.42	32.44	30.40	20.18	17.33	32.93
	$t_{n-1,1-\alpha/2}\, s/\sqrt{n}$	3.86	1.24	0.88	0.19	0.11	0.69
	SD	33.46	18.92	17.67	9.42	8.64	13.45
	$\rho_1,\rho_2,\rho_3,\rho_4$	62,78,42,93	61,78,41,92	61,76,40,90	58,72,39,86	52,66,35,78	61,76,41,92
0.29	$\bar{X}$	32.44	21.87	21.59	18.62	16.62	22.79
	$t_{n-1,1-\alpha/2}\, s/\sqrt{n}$	1.75	0.41	0.37	0.13	0.12	0.20
	SD	20.55	11.15	11.57	8.80	8.28	9.44
	$\rho_1,\rho_2,\rho_3,\rho_4$	57,72,38,85	57,72,38,85	57,71,38,85	56,69,36,82	51,63,33,75	57,72,38,86
0.22	$\bar{X}$	18.9	15.50	15.27	15.25	14.60	15.33
	$t_{n-1,1-\alpha/2}\, s/\sqrt{n}$	0.27	0.12	0.09	0.07	0.12	0.07
	SD	10.10	7.71	7.97	7.74	7.52	7.56
	$\rho_1,\rho_2,\rho_3,\rho_4$	45,56,30,67	45,56,29,67	44,55,29,66	45,56,29,66	42,53,28,63	44,55,30,67
0.18	$\bar{X}$	16.49	14.17	14.26	14.26	14.12	14.81
	$t_{n-1,1-\alpha/2}\, s/\sqrt{n}$	0.17	0.08	0.06	0.05	0.09	0.07
	SD	8.72	7.32	7.53	7.48	7.44	7.52
	$\rho_1,\rho_2,\rho_3,\rho_4$	37,46,25,55	36,45,24,55	37,46,24,55	37,46,24,56	36,45,23,55	36,45,24,54
0.15	$\bar{X}$	15.32	13.71	13.84	14.00	13.69	14.48
	$t_{n-1,1-\alpha/2}\, s/\sqrt{n}$	0.10	0.07	0.05	0.12	0.06	0.06
	SD	7.99	7.18	7.42	7.23	7.33	7.51
	$\rho_1,\rho_2,\rho_3,\rho_4$	32,40,21,48	31,39,20,46	31,39,20,47	32,39,21,48	31,38,20,46	31,38,20,46

- The simulation analysis reveals that the mean project throughput time is lesser than the mean applying CC methodology (Step S2), to the multi-project system (Figure 1, Table

1). It is 15.50 against 17.50. Nonetheless, 34% of the projects are expected to have a throughput time that exceeds the CCPM results since P(T>17.5)=0.340.

- Reducing the capacity buffer from the CCPM, it increase both project throughput time and standard deviation.
- Operating the system with No Control, mean and standard deviation were significantly higher than in CCPM. In the case of MinSLK was not significantly different from CCPM. In the case of Queue Size Control both mean throughput time and standard deviation got lower values.

PERSONAL OPINION

This paper is very contributive in two aspects:

- Firstly, we have a very significant impact into the literature CCPM because it focus on multi-project, which was not researched before so deeply.
- Secondly, surprisingly, the performance of CCPM in comparison with other methodologies, was not so good and we now that some other methodologies has similar and sometimes better performance than CCPM.

CONNECTION WITH NEXT PAPER

Since now on, we will focus on the mathematical part of CCPM, something that was not so clear in previous papers.

Also we will understand some insights of CCPM, we will analyze buffer sizing in more detail and relationship between CCPM and other areas such as engineer-procure-construct (EPC) projects.

12. A new heuristic for resource-constrained project scheduling in stochastic networks using critical chain concept

European Journal of Operational Research - M Rabbani et al - 2007

GOALS

- Presenting a new method based on resource-constrained project scheduling in stochastic networks using CC to minimize the expected project duration and its variance subject to resource constraints.
- Developing a new heuristic algorithm and comparing it with other existing methods.

MOTIVATION

- Resource-constrained project scheduling seems to be a challenging aspect to analyze.

ANALYSIS

The algorithm, the multiplication of average time, critically index and cruciality index of ready activities is used to select an optimal subset of them, using backward pass according to CCPM and removing Parkinson's Law, and "student syndrome". Priority levels determine the critical chain.

In comparison with Golenko-Ginzburg and Gonik model (the goal was to minimize the expected project time), they got better results even when adding buffers.

In comparison with William model (the goal was to minimize variance of the expected project time), they got better results.

CONSTRIBUTIONS

- A very explanatory graph with the changes in traditional PM system caused by implementing CCPM.
- A model that aims to minimize both expected project time and variance.
- Resource-constrained project scheduling is a Non Polynomial Completeness problem

PERSONAL OPINION

This paper proves that resource-constrained is in fact a problem that always will be a challenging for managers because it is a NP-Completeness. The rest of the analysis and literature review is very poor but the meet the goal they had set.

CONNECTION WITH NEXT PAPER

We cannot understand one of the basic problems of CCPM, without taking into account Parkinson's law because when we plan a project, we know that we have to set non critical activities as late as possible, but why? Because of Parkinson´s law.

13. Parkinson's law and its implications for project management

Management Science - Gutierrez, G. J., & Kouvelis, P. - 1991

GOALS

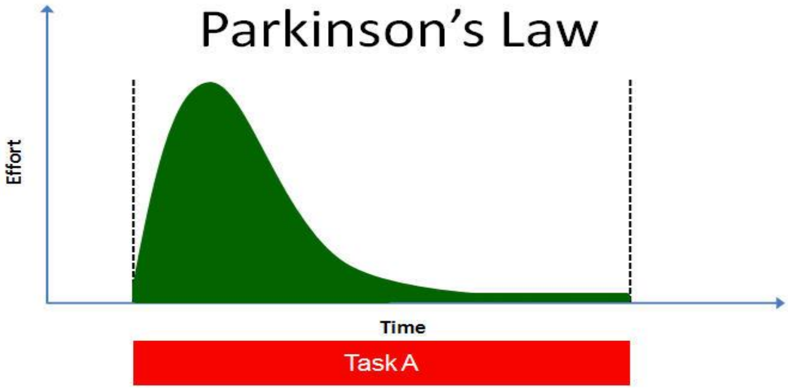
- Based on Parkinson's Law ("work expands so as to fill the time available for its completion"), analysis of the managerial implications of this behavior.

MOTIVATION

- Does CCPM take into account Parkinson's Law?

ANALYSIS

It was analyzed the implications of Parkinson´s Law during the scheduling. Why should we plan as late as possible but using buffers? Because if we plan as soon as possible, our resources will not be as efficient as we wish because of Parkinson´s Law. Why not as late as possible? Because we don´t want that this non-critical activity to become part of the critical chain. For this reason we add also a Feeding Buffer to prevent it.



CONSTRIBUTIONS

- They recommend scheduling all non-critical activities ALAP but using feeding buffers to prevent delays.
- Unlike PERT/CPM, CCPM takes into account Parkinson's Law.

PERSONAL OPINION

This paper is essential to understand the importance of buffering and planning when using not just CCPM but also all the methodologies since now on. Since Parkinson's Law was launched, this research is the most important connection with Project Management.

CONNECTION WITH NEXT PAPER

We know that Parkinson's Law and CCPM can be applied not only on scheduling in project management but also in some other areas such as procurement in engineer-procure-construct project as we can understand in the next paper.

14. Integrating supply chain and critical chain concepts in engineer-procure-construct (EPC) projects

International Journal of Project Management - KT Yeo - JH Ning 2002

GOALS

- Coupling Supply Chain Management (SCP) and CCPM.

MOTIVATION

- How to improve the performance of engineering and construction projects?

ANALYSIS

Analyze the characteristics of EPC projects and its relation with CCPM

Enumerates the causes of time wastage: Parkinson's law, Student's Syndrome, Multi-Tasking, Merging events.

CONSTRIBUTIONS

- Strategy to manage the movement and storage of materials and final product from suppliers, through the manufacturing process, to customers applying CCPM.
- The joint application of SCM and CCPM with special focus on procurement.
- TOC brings discipline in planning and execution of EPC Projects

PERSONAL OPINION

This paper is very specific. On one hand is very useful in this kind of project. On the other hand, it has not proved performance by using other methodologies.

CONNECTION WITH NEXT PAPER

Twelve years after Critical Chain (the book) Stratton makes an interesting recompilation of CCPM (theoretical and practical).

15. Critical chain project management theory and practice

Journal of Project Management and Systems Engineering - R Stratton - 2009

GOALS

- Analysis of Critical Chain (Book).

MOTIVATION

- CCPM has become the most famous methodology for planning.

ANALYSIS

Provides S&T guide in which it is illustrated a more comprehensive implementation methodology, and an updated thinking on how CCPM should be implemented (particularly, in relation to continuous improvement and flow control).

CONTRIBUTIONS

- CCPM has made a significant contribution to improving project management performance worldwide.
- The main reason for adopting CCPM is evidently enabling more predictable and shorter project lead times.

PERSONAL OPINION

This research does not include the flow planning of multiple projects. However, further research may test the guidance in more detail as well as elucidate the relationship between lean and TOC concepts.

CONNECTION WITH NEXT PAPER

Although CCPM has become the most famous methodology for planning, we have to highlight some chronic problems of this methodology and some solutions presented by Goldratt. It was studied just four years after Critical Chain (the book) but it is still valid.

16. On the merits and pitfalls of critical chain scheduling

Journal of operations management - W Herroelen, R Leus - 2001

GOALS

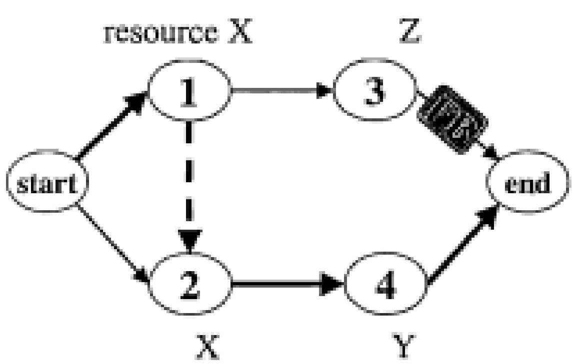
- Technical aspects of CC scheduling using simulation analysis.
- Highlights of the merits and pitfalls of CCPM.

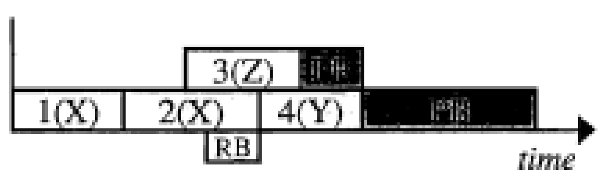
MOTIVATION

Why some researchers criticize (Raz et al for example) and other “love” this methodology?

ANALYSIS

Buffering is the main analysis of this paper





CONTRIBUTIONS

- The 50% rule for buffer sizing may lead to an overestimation of the protection leading serious time extensions.
- “2 Standard Deviation” method does not hold.
- Buffering is excellent for monitoring projects and setting realistic due dates. The danger lies in oversimplification. Branch and bound has a beneficiary effect on the project duration.

PERSONAL OPINION

Herroelen et al, four years after Critical Chain (the book) understood perfectly the advantages and disadvantages of this methodology. He strongly agrees with the use of buffers but he distrusts Goldratt when he proposes using the “50% rule”. If we pay attention that this paper was written 15 years ago, we can appreciate that Herroelen was the best interpreter of CCPM.

CONNECTION WITH NEXT PAPER

We can see in this paper that buffering has the best and the worst opinions on this methodology. All the researchers agree that buffering is the best idea of CCPM but most of them criticize the way to calculate it.

17. A new approach for buffer sizing in critical chain scheduling

Industrial Engineering and Engineering Management - Ashtiani, B., Jalali, G. R., Aryanezhad, M. B., & Makui, A - 2007

GOALS

- Criticizing “50% buffer sizing” mentioned by Goldratt (half of the non-critical tasks’ duration that join the CC as the feeding buffer’s size increase linearly and it may cause large excessive amount of protection).
- Finding a new method assuming lognormal distribution for task completion time.

MOTIVATION

- 50% Buffer Sizing seems to be an inaccurate way to calculate buffers.

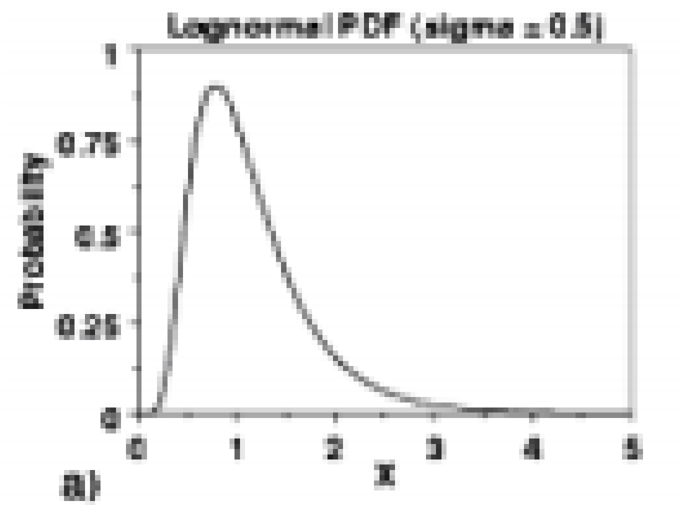
ANALYSIS

The actual buffer's size is: ½ of the sum of the activity durations in the chain of activities that precedes the buffer.

Buffer's size (alternative): to sum the DS, use the square root of the sum of the squares (law of aggregation).

Table III
VALUE OF σ

Risk	σ
Very High	0.5
High	0.4
Medium	0.3
Low	0.2
Very Low	0.1



RESULTS OF SIMULATION

#	RSEM		Proposed Method	
	Ave. Buffer	Protection	Ave. Buffer	Protection
1	5.46	83%	8.04	95%
2	3	92%	4.29	97%
3	7.45	100%	11.25	100%
4	2.96	100%	4.3	100%
5	9.68	90%	14.64	100%
6	2.14	96%	3.19	100%
7	9.8	98%	14.86	99%
8	3.83	96%	5.55	99%
9	6.82	92%	10.12	97%
10	5.12	96%	7.7	100%

CONTRIBUTIONS

- A new method to size the buffer, using lognormal distribution, based on Root Square Error Method (RSEM).

PERSONAL OPINION

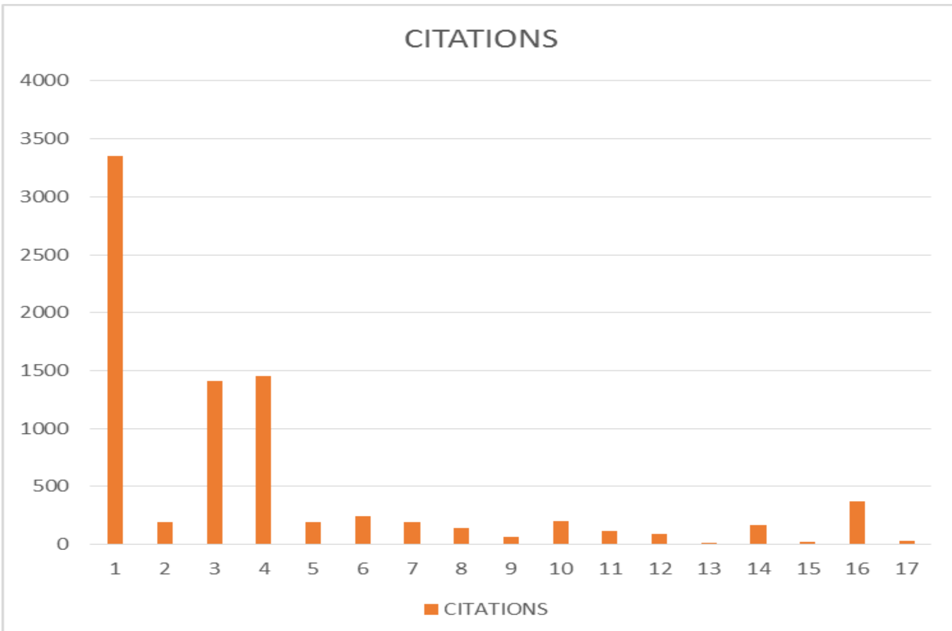
- This was a very simple but effective analysis. They showed an improvement with this new approach. Further research could analyze other statistic distributions for task completion time.

SUMMARIZE

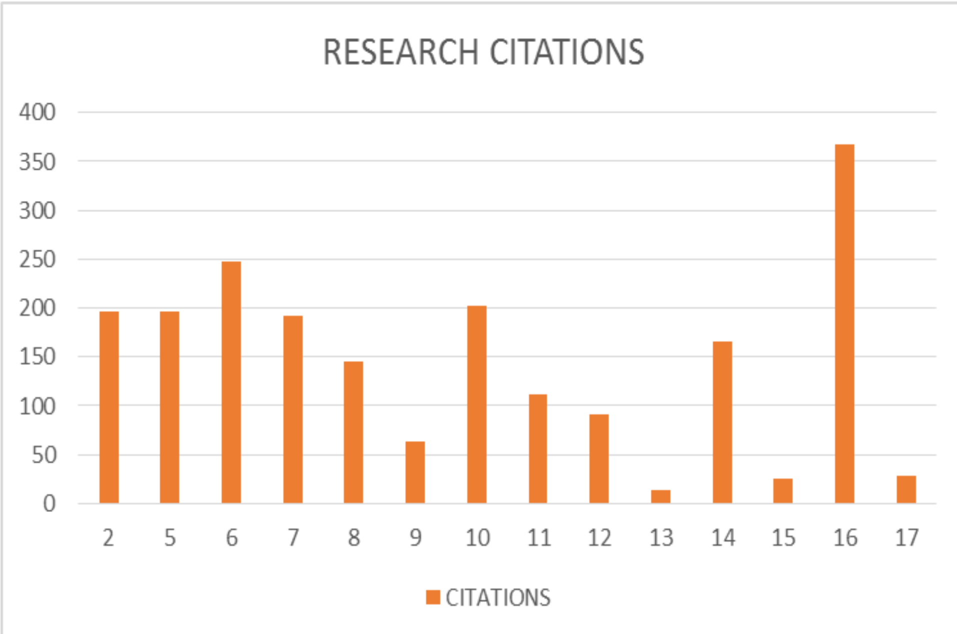
#	Resource analysis	5 Steps for CCPM	New Methodology	TOC and Buffer Analysis	Implementation examples	Difference between CCPM and CPM	Difference between CCPM and other methodologies	Integrating CCPM with other areas
1	X	X						
2	X		X					
3	X	X		X				
4	X	X	X	X	X			
5	X	X		X	X	X		
6	X	X		X	X	X		
7	X	X		X	X			
8	X			X	X	X		
9				X	X	X		
10				X	X			
11	X			X	X		X	
12	X	X		X				
13	X							
14		X		X	X			X
15	X	X		X	X	X		
16	X	X		X		X		
17	X	X		X				

CITATIONS

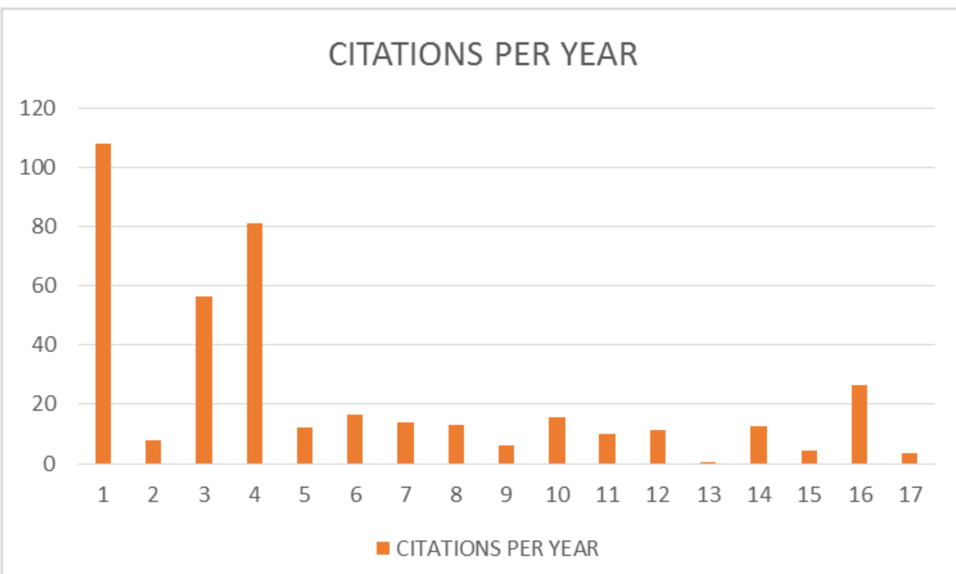
BOOKS AND RESEARCH CITATIONS



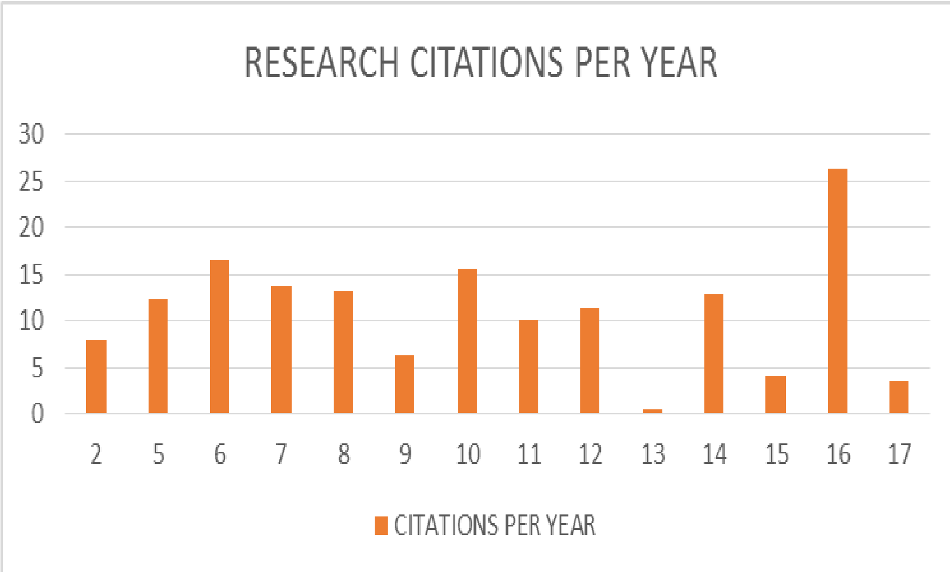
ONLY RESEARCH CITATIONS



BOOKS AND RESEARCH CITATIONS RATE



RESEARCH CITATION RATE



We can identify something that reflects the importance of CCPM. Since 1984, when The Goal was launched into the market, each year more than 100 researchers have to cite this book and more than 80 cite Critical Chain.

OTHER IMPORTANT RESEARCH

Many other important research were carried out since 1984 about CCPM. Most of the research analyze different ways mathematical models for sizing buffers and give a critical point of view of the methodology. The most new one, developed at the Technion was in 2015 by Balouka, Cohen and Shtub.

#	RESEARCH	AUTHOR	YEAR
18	A branch-and-bound procedure for the multiple resource-constrained project scheduling problem	Demeulemeester, E., & Herroelen, W.	1992
19	Resource-constrained project scheduling: a survey of recent developments	Herroelen, W., De Reyck, B., & Demeulemeester, E.	1998
20	Some constraints on the theory of constraints: Taking a critical look at the critical chain	Pinto, J. K.	1999

21	Estimation of project buffers in critical chain project management	Shou, Y., & Yao, K. T.	2000
22	PMBOK and the Critical Chain Scheduling with critical chain-is the concept new or only a new gimmick? And should it be included in the PMBOK® Guide?	Globerson, S.	2000
23	Critical chain project scheduling-Do not oversimplify	Herroelen, W., Leus, R., & Demeulemeester, E.	2002
24	An investigation of buffer sizing techniques in critical chain scheduling	Tukel, O. I., Rom, W. O., & Eksioglu, S. D.	2006
25	Extending the Multimode Resource-Constrained Project Scheduling Problem by Including Value Considerations	Balouka, N., Cohen, I., & Shtub, A.	2015

SOFTWARE

This is a list of the software for CCPM mentioned in some papers. It was added new programs and applications developed by different companies:

- MS Project (1998…2010)
- Prochain Solutions (1999)
- Concerto (1999)
- Scitor (2000)
- PTB Training Simulator (2005)
- Agile-CC (2008)
- BeingManagement 2 (2010)
- Exepron (2011)
- LYNX CC, PSNext, CCPM+, Aurora-CCPM, etc.

- 19 Applications for Smartphones

CONCLUSION

It is still CCPM one of the most important methodologies used in the industry. Nevertheless, there are some other methodologies with similar and even better performance in multi-project.

Buffering is the more controversial part of CCPM. Although it is the main advantage of CCPM we do not have an optimal way to calculate and we will not have an optimal since resource-constraint is a NP-Completeness problem.

I should mention that CCPM has to be investigated even deeper. Further researchers could analyze new ways to approach the buffer problem and connection between CCPM and other areas such as Queue Theory since we have many implication of this methodology if we want to optimize queues, services time, non-abandonment and customer satisfaction.

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