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A Study of the Critical Chain Project Management Method Applied to a Multiproject System

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Abstract

In 1997, Eliyahu Goldratt proposed a method called critical chain project management (CCPM) to minimize the inefficiencies identified in traditional project management. The project management community accepted the proposed method as a viable alternative. However, to allow its implementation with a multiproject system, more research was necessary. Seeking to identify the key factors that influence the performance of the multiproject system applying the CCPM method, we performed a case study. Logistic regression analysis showed that applying the CCPM method in a multiproject system allows for better time estimation of activities and facilitates the allocation of critical resources.

Keywords

project scheduling, Critical Chain Method, multiproject management, resource allocation, logistic regression analysis

Introduction

Although techniques developed in the 1950s—including the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT)—are usually applied to time management in projects, projects still fail to achieve their time goals.

In 1997, Eliyahu Goldratt proposed a method based on the fundamentals of the Theory of Constraints (TOC) called critical chain project management (CCPM) to minimize the inefficiencies identified in traditional project management methodology. The proposed method was accepted by the project management community as a viable alternative that could bring real gains. The proposed method was included as a schedule network analysis technique in *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)* – Third Edition (2004). The method has some issues that should be considered regarding its implementation when using the CCPM method in a multiproject environment (Lechler, Ronen, & Stohr, 2005; Raz, Barnes, & Dvir, 2004).

A multiproject environment is the formation of a network of projects of varying sizes and importance that depend on the same set of resources and are characterized by high uncertainty and high complexity. In these environments, managers are exposed, along with their staff members, to constant changes throughout the project life cycle (Miloševic & Patanakul, 2002). Organizations that deal with multiple projects simultaneously are often accused of failures in the time management of activities (Wei-Xin, Xu, Xian-long, & Lei, 2013).

To conduct a comprehensive analysis and understand the behavior of the CCPM method in a real multiproject environment, we performed a case study in a tooling manufacturing company for the construction industry facing a complex environment with projects competing for the use of resources. The contribution of this work is based on the application of a set of techniques and methods through a sequence of steps that allow the identification and analysis of the key factors that influence the time estimation of activities when the CCPM method is used.

The aim of this study is to identify the key factors that influence the performance of the critical chain project management method for this case by answering two research questions:

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1. How is the time estimation of activities done using the CCPM method?
2. What is the behavior of the critical resource in the multiproject environment when the CCPM method is used?

In addition to this first introductory section, the text is organized as follows: the second section provides a literature overview; the third section presents an explanation of the methodology used; a description of the case study appears in the fourth section; and, finally, in the fifth section the conclusions are presented.

Literature Review

Critical Chain is a project management method that focuses primarily on the management of the duration of activities, considering the allocation of resources, and is based on the principles of the Theory of Constraints (TOC). This method was initially proposed by Goldratt (1997) and later detailed by others (Blackstone, Cox, & Schleier, 2009; Leach, 2000; Peng & Jin, 2009; Steyn, 2000).

To perform any activity in a project, two things are necessary: the activity input from a predecessor and a resource to perform the activity; thus, the critical chain method includes both resource and activity logic constraints to complete the project on time or earlier. For Leach (2000), the evident constraint of a unique project is the chain of activities that takes the longest to complete. In environments with multiple projects, assuming these projects are carried out at the same time, the resources (people) are typically divided between the projects leading to multitasking, thus reducing the possibility of finishing the activities in the time scheduled. Evidently, at least one of these resources should be the capacity constraint of the system, so the company's resource constraint (people) becomes the drum for scheduling multiple projects.

Since its proposal, the CCPM method has been accepted by part of the project management community, as evidenced in work published by Rand (2000); Umble and Umble (2000); Newbold (2008), Tian, Zhang, and Peng (2010); and Butler and Richardson (2011). These authors advocate the application of the CCPM method as a way to present concepts they consider innovative: a reduction of the initial time estimates \to avoid the appearance of the student syndrome and Parkinson's law, by using time buffers at the end of the project and providing ways to address uncertainty in activity planning. In addition, resource bottlenecks as system constraints and managing the project through the indicators of its time consumption should be taken into consideration. These considerations will provide a vision of the entire system, not only focusing on each activity individually, but on the progress of the project as a whole.

Acceptance of the CCPM method by the project management community was evidenced by the fact that it was included in the third edition of the *PMBOK® Guide* (PMI, 2004) and continues to be cited within the Develop Schedule process as a schedule network analysis technique in the Project Time Management processes in the fifth edition of the *PMBOK® Guide* (PMI, 2013).

Furthermore, there is another part of the scientific community that has questioned its basis and application, as can be seen in the work published by Herroelen, Leus, and Demeulemeester (2002); Raz et al. (2004); Herroelen and Leus (2005); and Lechler et al. (2005). These researchers argue that the concepts considered to be innovative are not totally new because they were obtained from concepts or theories formulated earlier and that more empirical evidence and scientific studies are needed to demonstrate the efficacy of the CCPM method.

In the literature review, we have found that most of the work focuses on the analysis of the unique aspects of the CCPM method, such as time buffers (Bie, Cui, & Zhang, 2012; Peng, Junwen, & Huating, 2007; Tukel, Rom, & Eksioglu, 2006) and the application to individual projects (Balakrishnan, 2010; Long & Ohsato, 2008; Peng & Jin, 2009).

These publications have made important contributions to the development of the CCPM method, but they have not shown applications in a real multiproject environment nor have they identified the key factors that may affect the performance of the critical chain project management method.

Research Methodology

Due to the divergence of ideas between those who accept or reject the CCPM approach, as well as the lack of published papers analyzing real applications across multiple projects, we decided to focus this case study on two stages. First, on the identification and definition of the key factors (independent variables) that can affect the performance of a multiproject system, and second, by conducting an analysis based on statistical tools to identify relationships between these factors and system performance in a real case, as shown in Figure 1.

Based on the description in Figure 1, during the first stage, which lasted nine months, it was necessary to identify from the literature review and field study the factors that mostly influenced the performance of the estimated time in the schedule of activities of the projects. To this end, a set of 17 projects were chosen, including 340 activities in total, which were performed in parallel where 20 resources were shared. During this stage, the company managed their projects, as traditionally done, by applying the critical path.

During the second stage with a duration of five months and using techniques of action research, a group of four projects with 13 shared resources and a total of 120 activities were studied. For this group of projects, the CCPM method was applied, including consumption rate of the project buffer.

The four projects chosen for the second stage of the case study were projects that the company needed to carry out as part of its development strategy to enter new markets, which reduced the risk of having the case study canceled because of a change in the company's priorities.

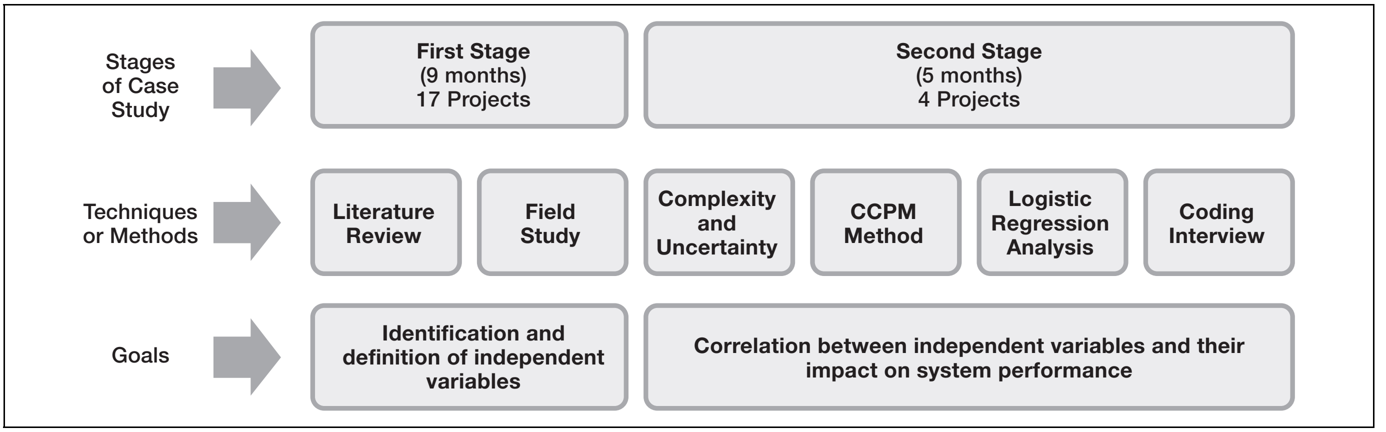

Figure 1. Stages, techniques, and goals for the case study.

During this second stage, the independent variables selected for analysis were translated into a questionnaire in order to collect data and the results were evaluated based on two analytical techniques: logistic regression analysis and expert judgment (coding interviews). Both techniques are discussed in the fifth edition of the *PMBOK® Guide* (2013, PMI) and are used in this study with the purpose to formalize the completion of the projects and validation of results obtained.

Case Study

The case study involves a mid-sized company with 185 workers in Brazil that develops and manufactures manual and electric tools for the construction industry. The reasons that led us to select and study this case were: (1) product development presents a complex environment because of the competition for the availability of resources in projects running in parallel; (2) the high degree of uncertainty and complexity present in all projects; and (3) the first stage of the research revealed that the difficulties regarding the administration of the projects are similar to those reported in the literature and benchmarking surveys. Having said that, we believe that these conditions are similar to those that can be found in other companies, so the same method can be applied.

In this section, the techniques and methods applied in the two stages of the study are detailed, starting with the definitions of independent variables, verification of complexity and uncertainty, planning and control using the CCPM method, and analysis and validation of results using logistic regression and expert judgment (coding interview).

Defining Independent Variables

Taking into consideration the literature review, we started with the main factors that impact the duration of a project as described in the papers of Raz et al. (2004) and Lechler et al. (2005). From the field study developed in the first stage, five impact factors were identified as those that impact project deadlines (see Table 1).After analyzing which of the identified factors would have their impact on the project deadlines measured (in other words, factors that can be recorded as events that do or do not happen during the performance of an activity) a set of seven independent variables were selected: scope not defined or changed (X_1), lack of risk analysis (X_2), precise amount of safety margin (X_3), inclusion of new projects (X_4), rework (X_5), resource leveling (X_6), and multitasking (X_7).

Impact factors, such as corporate culture (X_8), organizational policies (X_9), and performance of resources (X_{10}) are factors that are parts of the human behavioral aspect of the members of the project management team; in this case study, it was determined that their identification and registration are more complicated than with the seven independent variables selected for logistic regression analysis. More specifically, with reference to performance of resources (X_{10})—because it was the first time that the CCPM method was applied in the company, it was not considered appropriate to monitor the performance because it could have led to team member resistance.

Furthermore, we consider that five (X_1, X_2, X_4, X_5, and X_7) of the seven variables identified in the first stage of the field study, reflect behaviors of the corporate culture and organizational policies of the company.

Assessment of Complexity and Uncertainty

Complexity and uncertainty are two of the main characteristics of any project and, according to Goldratt (1997) and Leach (2000), because the CCPM method focuses on eliminating the additional security time, it is suitable for application in environments of projects with high complexity and uncertainty.

Complexity and uncertainty in project management have been analyzed by other authors, however, none of the proposed scale of measurement addresses these two characteristics at the same time (Pich, Loch, & De Meyer, 2002; Sinha, Thomson, & Kumar, 2001; Vidal, Marle, & Bocquet, 2011).

Vanhoucke (2013) proposes a way of mapping projects in two dimensions—complexity and uncertainty—in order to put the techniques or methods for project management that must be

Table 1. Main Impact Factors in Project Deadlines

Impact Factors in Project Deadlines	Author/Source: Raz, Barnes, and Dvir (2004)	Author/Source: Lechler, Ronen, and Stohr (2005)	Author/Source: First Stage Field Study	Selected for Statistical Analysis: Yes	Selected for Statistical Analysis: No
Scope not defined or changed (X_1)			x	x	
Lack of risk analysis (X_2)			x	x	
Precise amount of safety margin (X_3)	x	x		x	
Inclusion of new projects (X_4)			x	x	
Reprogramming (X_5)			x	x	
Resource leveling (X_6)	x			x	
Multitasking (X_7)	x	x	x	x	
Corporate culture (X_8)		x			x
Organizational policies (X_9)	x				x
Performance of resources (X_{10})	x	x			x

used according to the type of project into perspective. In this proposal, the CCPM method is a scheduling approach with the main emphasis on project resources and buffer management and is used to assess the performance of a project in environments with a high degree of complexity and uncertainty.

To assess the degree of complexity and uncertainty of the projects involved in the study, we applied the measurement scale proposed by Pinto, Novaski, Anholon, and Besteiro (2014). These authors identified a set of 20 variables that represent the complexity and uncertainty in projects.

The procedure for applying a measurement scale of complexity and uncertainty is to have responses from project team members, using a questionnaire with 10 questions related to complexity, for example: size of the project, type of innovation or number of project stakeholders; and another 10 questions related to uncertainty, for example: project duration, changes in the project scope or project risks.

Each question has a score that is calculated at the end and results in the production of a matrix that converges the classification into a single point, in relation to complexity and uncertainty, in the Cartesian plane. This helps us to understand how complex and uncertain the projects are.

The result of the application of the measurement scale for the four projects in the second stage is shown in Figure 2, and was answered by eight members of the project management team.

The results in the scale highlighted that the chosen projects had uncertainty and complexity degrees varying from medium to high, justifying use of the CCPM method.

Use of this scale is helpful because it enables the setting of a benchmark to prioritize resources for projects, depending on their uncertainty and complexity. In this case, to scale the critical resource within the multiproject system, we should present the following order: P-01, P-02, P-03, and P-04, which prioritizes projects from least complexity (Project P-01) to the ones of most complexity (Project P-04).

The Critical Chain Project Management Method

The programming of activities is done by applying the concepts of the CCPM method, specifically to estimate the timing of activities, allocation of resources, definition of time buffers, and scaling of critical (bottleneck) resources (Leach, 2000; Newbold, 2008). The steps in the application of the method, with their main considerations, are described in Table 2. One of the criticisms made of the CCPM method is whether the rule to reduce 50% of the estimated initial time is the right amount to remove from the safety margin included in planning time activities. From our point of view, this rule can be taken as a starting point to reduce time estimates; however, the knowledge we have about the realization of the activities must be considered. In other words, in an activity where the knowledge in the company is considered high and based upon available historical data that enable an accurate measure on activity duration, this rule would not make sense. However, for activities considered new for the company or with a high degree of uncertainty, we can apply this rule.

Relating risk and uncertainty, Perminova, Gustafsson, and Wikström (2008) affirm that the risk of a project is a factor that gives rise to uncertainty, present in different ways in all projects, which can be described respectively as cause and consequence. Therefore, we propose that based on risk assessment, the application of this rule is dependent on the maturity of the company for each activity.

For this case study, we consider that an activity with a low risk identification may have a decrease of between 0% and 10% in its initial time estimate. For an activity with a medium level of risk identification, the time reduction may be between 10% and 25%. Finally, for an activity with a high level of risk identification, the time reduction may be between 25% and 50%.

The results for the difference of the duration of the activities for each resource are presented in terms of the arithmetic mean in Table 3. None of the duration of activities was greater than 20% of the total duration of any project, as recommended by

Project	Complexity	Uncertainty
P-01	81	121
P-02	100	132
P-03	121	165
P-04	143	148

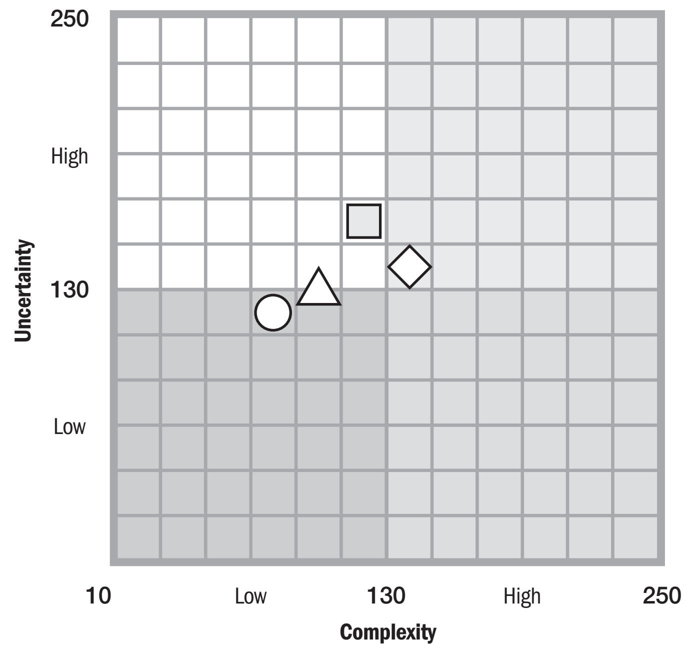

Figure 2. Measurement scale of the complexity and uncertainty of four projects.

Table 2. Steps and Descriptions of the CCPM Method

Steps of the CCPM Method	Descriptions and Considerations
1. Define the priority for each project	• Identify the complexity and uncertainty degrees of the project portfolio. According to the measurement scale, define the priority of the projects, considering that of greater complexity as a priority. • Identify the critical resource of the system, such as the one with the greatest number of work hours.
2. Prepare the schedule of each project and program it using the CCPM method	• Determine the critical chain for each project considering the dependencies between activities and the chosen critical resource. • Define the reserves or buffers (feeding buffer, project buffer, and resource buffer).
3. Stagger the projects according to the priority	• Eliminate resource conflicts • Add resource buffer to the critical resource, in order to balance the distribution of resources shared by two adjacent projects.
4. Control schedule, through the graphics of the time buffer consumption rate	• Update the progress status and the time buffer consumption. • Make decisions based on the state of consumption of the buffers. • Present the results of the indicators (consumption of the buffers) to the project team members.

Table 3. Comparison of the Planned Workload

Identification of the Resource	Risk Assessment	Activity Time Traditional (h)	Activity Time CCPM (h)	Difference (%)
D1	Low	1,736	1,736	0.0
E1	High	1,156	828	28.4
S1	Medium	912	800	12.3
Q1	High	752	400	46.8
E2	Medium	684	584	14.6
E3	Low	528	490	7.2
P1	High	288	144	50.0
M1	Low	200	180	10.0
U1	Medium	124	100	19.4
Pr1	Low	72	72	0.0
E4	Low	64	58	9.4
Pk1	Low	40	40	0.0
Mk	Low	16	16	0.0
Total		**6,572**	**5,448**	**17.1%**

Leach (2000).The resources involved in a multiproject system came from the areas of engineering (E1, E2, E3, E4), production (P1, Pr1), quality control (Q1), marketing (Mk), purchasing (S1), material planning (M1), packaging (Pk1), machining (U1), and the outsourcer manufacturer of injection molds (D1), as shown in Table 3.

In Table 3, for each resource we show the differences between the duration of the activity estimated in the traditional way—the critical path method—and in another way, using the CCPM method that stipulates taking a percentage of the

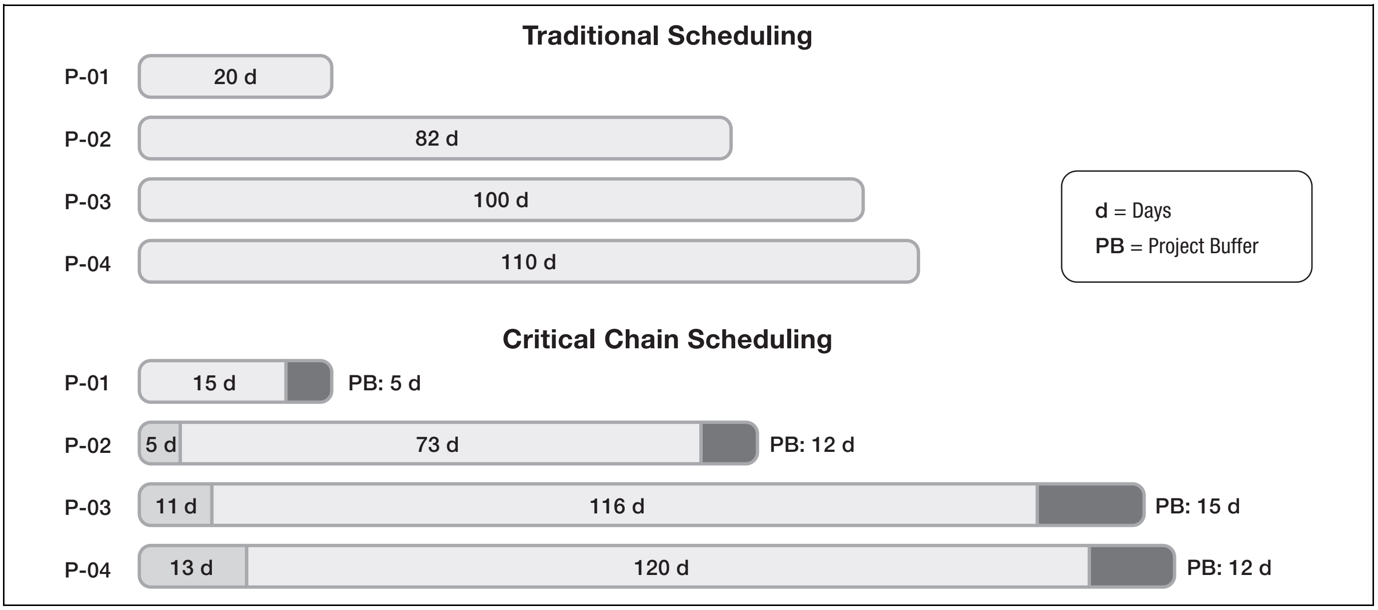

Figure 3. Comparisons of time estimated by the traditional (CPM) and CCPM methods.

duration originally estimated. The difference in hours planned using the two methods is 1,124 hours, which is equivalent to 17.1% of the duration estimated by the traditional method. The following observations can be made:

- D1 is the resource with the highest number of hours (1,736 hr) and corresponds to an external supplier. Although this feature could be considered a bottleneck resource, it was not chosen to be the critical resource because the company did not have direct control over its activities. Moreover, we did not consider the reduction of hours estimated initially, since the history of service demonstrated compliance with the agreed-on deadlines. The same happens with resources Pr1, Pk1, and Mk.
- Resource E1 has been chosen to be the bottleneck resource (828 hr), or critical resource, for having the highest number of hours. Resource E1 is the drum for scheduling a multiproject system and is responsible for carrying out the 46 activities that make up the critical chain.
- Resources Q1 (400 hr) and P1 (144 hr) had their number of hours decreased by 46.8% and 50.0%, respectively. This happened because of the greater risk assessment.
- The resources E2, E3, E4, M1, S1, and U1 are not critical resources and their decrease in the estimated duration was between 0% and 10% (low risk) and between 10% and 25% (medium risk), respectively.

After applying the CCPM method, a new time schedule to carry out the projects was obtained. The results are shown in Figure 3, where it is possible to see the set of four projects and the comparisons between traditional and CCPM methods, regarding the start and end dates of projects, and considering all available resources for each project.

The following observations can be made from Figure 3:

- Disregarding the inclusion of the time buffer on projects P-01 and P-02, their duration has decreased, whereas the times of projects P-03 and P-04 have increased. When we considered the time buffers, however, the times of projects P-02, P-03, and P-04 increased. This behavior goes against what is argued by proponents of the CCPM method, in the sense that the decrease of 50% of the time of critical chain activities shortens work schedules. In our view, we can apply this concept to individual projects, but for the projects analyzed in this case study, not necessarily, since it depends on the allocation of resources, mainly the bottleneck resource (see Figure 4).
- The increase of the initial estimation of time for the projects is because the scheduling or allocation of critical resources (E1) was made considering three key aspects: the elimination of multitasking, the prioritization of the project (according to the scale in Figure 1), and the availability of a resource buffer, when the critical resource must switch between one project and another (see Figure 4).
- A major advantage obtained from the decrease in time for most activities of the critical chain and the assignment of resources, especially the bottleneck resource, was the elimination of multitasking, although this staggering increased the estimated time of completion, as seen with projects P-02, P-03, and P-04. It is preferable to work with a longer, but real estimated date of completion than to control multitasking.
- Projects P-03 and P-04 obtained the lowest percentage of time buffer for projects: 11.4% and 10.0%, respectively. The reason for this is that these projects have a

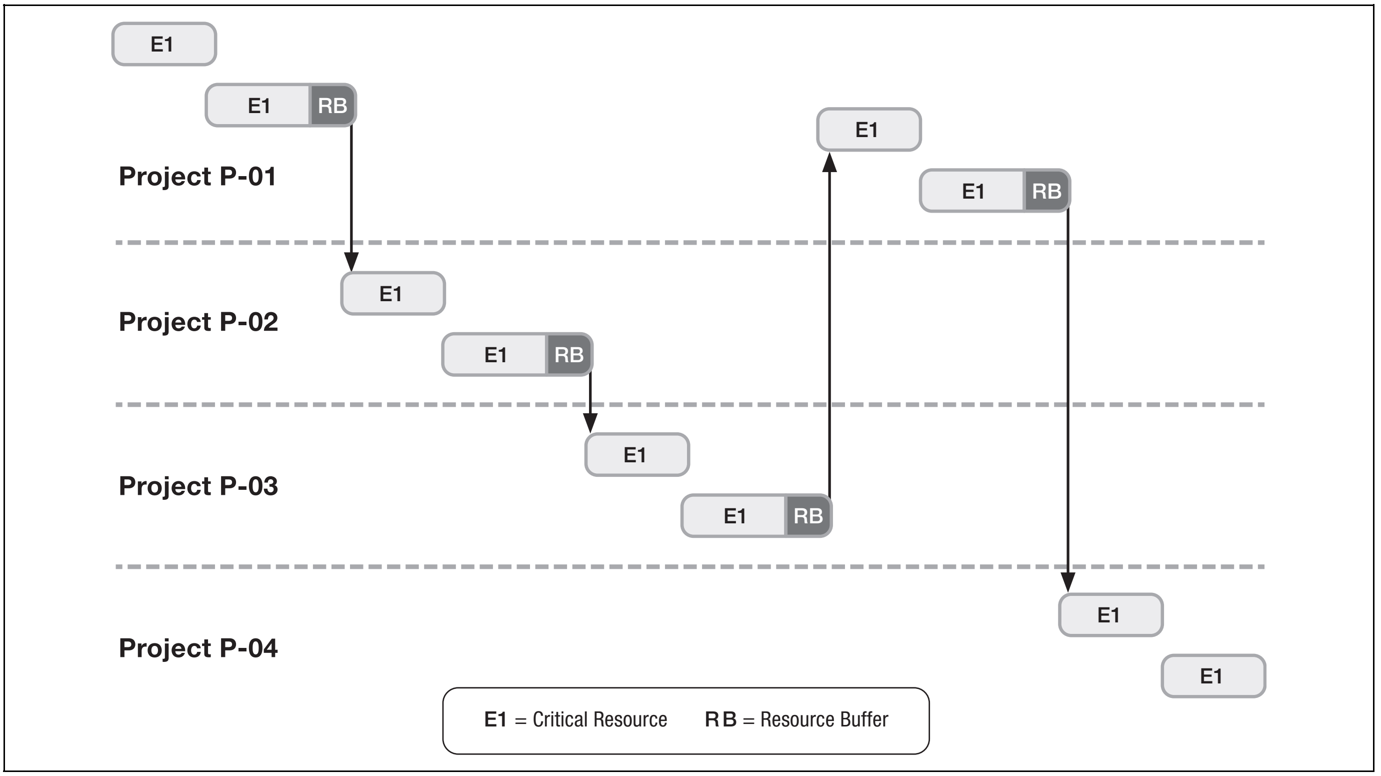

Figure 4. Allocation of critical resources on a multiproject system.

high demand of time related to external services that they have no authority over.

- Project P-01 has the same start date in the two schedules, but P-02, P-03, and P-04 projects are scheduled 5, 11, and 13 days later, respectively. The reason for this is because the resource (E1) is used at the start of all projects, and the project sequence follows the order P-01, P-02, P-03, and P-04.
- The increase in the initial estimation of time for the project is because the scheduling or allocation of critical resources (E1) was made considering three key aspects: elimination of multitasking; prioritization of the project according to the scale in Figure 1; and availability of buffer resource, when the critical resource must switch between one project and another, as shown in Figure 4.

Project Control

For monitoring and control of the multiproject system the project schedule and the graphics of the consumption rate of time buffers were used, which were examined at the weekly meetings during a period of five months.

In Figure 5, the estimated and the real times are compared in relation to the behavior of the workload level over the life cycle of a multiproject system. The estimated time (110 days) applying traditional method (Critical Path) is also presented as a reference.

By analyzing Figure 5, we can note that the initially planned time (CCPM method) has a total duration of 145 days, whereas the real one had 125 days, that is, 13.8% less. When the total hours are compared, it is observed that the initial estimate was 5,448 hours, whereas the actual estimate was 3,632 hours, that is, 33.3% less.

In Figure 5 the greatest difference between the two working load curves (CCPM method) was between days 20 and 40. During this period, projects P-03 and P-04 had delays because of disruptions caused by the appearance of unplanned tasks, related to other company activities, meaning that some activities of the critical chain were interrupted, and when restarted had less time, resulting in the requirements not being fully addressed, rework being required and a decreased work rate.

The projects used in this case study were of strategic priority and the company's board of directors was directly involved, so actions were taken to stop the influence of external factors, which is why we can observe that the pace of the work recovered from day 45.

Even with the decrease of the pace of work, the projects were able to finish within the planned time frame. This may be an indication that the initial estimated time of the project has built-in security, as explained by Leach (2000). In this case, it was 13.8% less than the estimated time, which provides evidence that the CCPM method reduces the embedded additional security on the estimated time of initially planned activities, thus minimizing the impact that the student syndrome and Parkinson's law have over the estimated time of activities (Goldratt, 1997).

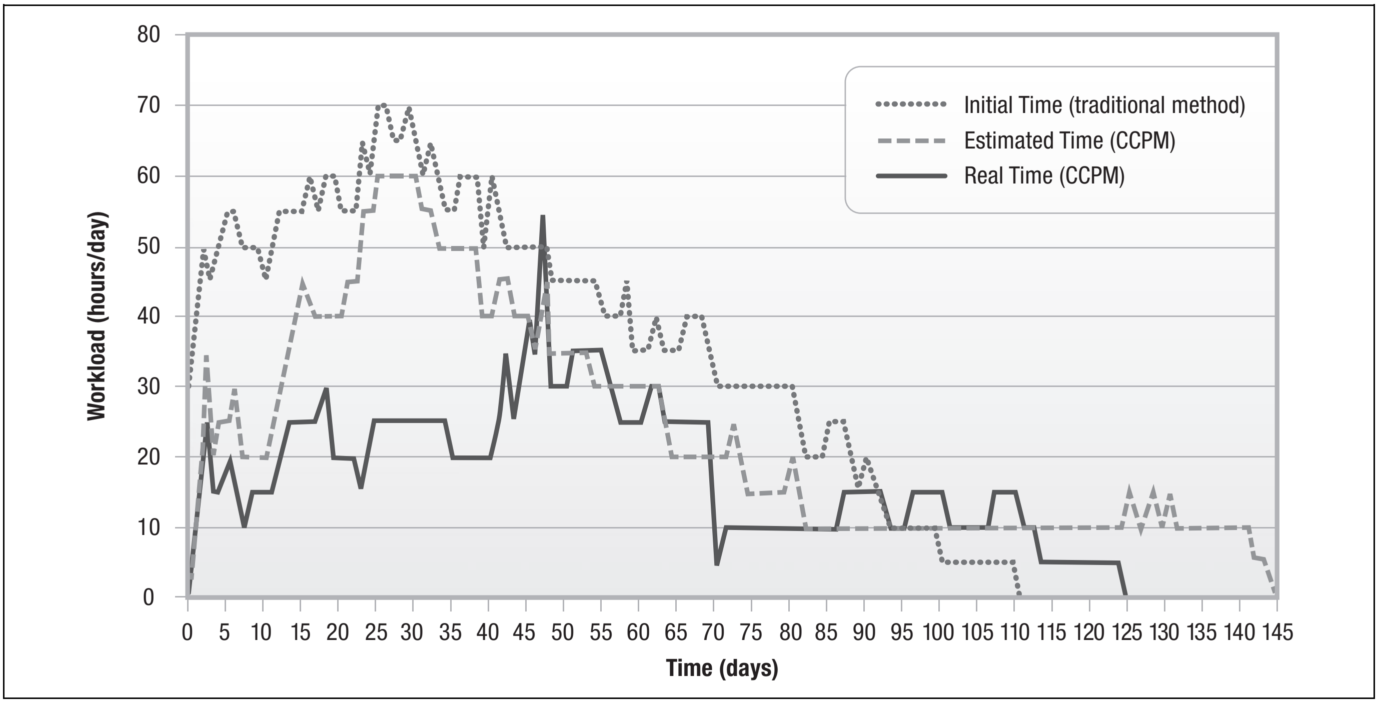

Figure 5. Workload level over the life cycle of a multiproject system.

Validation of Results

With the purpose of formalizing the completion of the projects involved in the case study, the fifth edition of the *PMBOK® Guide* (PMI, 2013) guidelines (4.6 Close Project or Phase, p. 100) were followed for the application of techniques and tools to close the project, using analytical techniques and expert judgment.

Analytical techniques were based on the application of logistic regression to identify the variables that most affect the performance of the system when the CCPM method is used. The expert judgment focused on the confirmation that the CCPM method was performed according to the appropriate practices, and that these practices are also applied in other companies that have a more mature level of project management with proven results.

Table 4. The Questionnaire Used to Record the Variables Information

While Performing the Activity, Did Any of the Variables Listed Below Appear?			
Independent Variable	Description	Yes	No
X_1	No defined or changed scope		
X_2	Lack of risk analysis		
X_3	Precise estimate of safety margin		
X_4	Inclusion of new projects		
X_5	Rework		
X_6	Resource leveling		
X_7	Multitasking		
The activity was completed in the planned time? (Dependent variable)			

Analytical Techniques: Logistic Regression

Logistic regression is the type of multivariate analysis that allows the use of a mixture of categorical and quantitative data as influencing variables. In other words, it expresses the probability of an event happening according to specific variables (Kleinbaum & Klein, 2010). With only a few studies in the literature, its application in project management is still incipient (Hammad, Alhaj, Sweis, & Sweis, 2010; Kompella, 2013).

The procedure for applying logistic regression analysis in this study is as follows: first, information on the appearance of independent variables is recorded in a questionnaire (see Table 4) and whether or not the activity has been completed on time. Second, the data are entered in the form of spreadsheet in the software Minitab® (see Table 5). Third, the data are processed in the software using the binary logistic regression option, and the results are evaluated in terms of level of significance, the odds ratio relationship (see Table 6), and the fit test.

To check if the impact of the seven independent variables (see Table 1) was in compliance with the planned time (dependent variable), a questionnaire was applied (Table 4) using a dichotomous nominal scale (Yes = 1; No = 0) for both independent and dependent variables. Each of the 46 activities of the critical chain was monitored in weekly meetings by controlling the time and scoring in the questionnaire if the activity had met the scheduled deadline and if any of the seven independent variables had appeared.

Table 5. Sample Records of the Data File for Logistic Regression Analysis

	Independent Variables							
Task No.	X_1	X_2	X_3	X_4	X_5	X_6	X_7	Dependent Variable
1	0	0	0	0	1	0	1	0
2	1	0	1	1	1	0	0	0
3	0	0	0	0	0	0	0	1
4	0	0	1	0	0	0	0	1
5	0	0	1	1	1	0	0	0
6	0	0	1	0	0	0	0	1

Table 6. Estimated Coefficients of the Independent Variables

Predictor	β_i	S.E	Sig.	Odds Ratio	P-Value
X_1	–21.010	13840.6	0.999	0.00	0.018
X_2	–0.760	0.832	0.361	0.47	
X_3	0.443	0.807	0.583	1.56	
X_4	0.102	0.984	0.917	1.11	
X_5	–2.344	0.931	0.012	0.10	
X_6	0.399	1.140	0.726	1.49	
X_7	–0.735	0.875	0.401	0.48	
Constant (α)	2.242	0.9762	0.022	-	

Note. β_i – Coefficient; S.E – Standard Error; Sig. – Significance

Table 5 shows an example of how the data were collected by the questionnaire, using data from six activities or tasks, belonging to the P-02 project. Table 6 shows the results corresponding to the logistic regression analysis for 46 activities.

Analyzing the data in Table 6, totaling 322 responses (7 influence variable, 46 activities) for a confidence interval of 95% (Sig. = 0.05):

- P-value is 0.018, which is smaller than 0.05, meaning that there is a significant relationship between the response and at least one of the parameters or independent variables.
- The X_5 (0.012 <0.05) and Constant (α) (0.022 <0.05) parameters are the most significant ones. The other parameters did not show a significant relationship between the response and each other.
- The X_5 parameter (Coef. $= -2.344$), representing the influence of rework, has a negative value, meaning that when this parameter appears, the completion of the activity is less likely. This represents the restriction of the system.
- The X_5 parameter (Odds Ratio = 0.10) is less than one (1.0), which means that the smaller its value, the lower the probability of finishing the work on time.

Once each activity could be impacted by seven independent variables, for the 46 activities analyzed (that is 322 possibilities), a total of 104 occurrences were recorded: 30 responses related to rework of activities (X_5), 19 related to multitasking (X_7), 16 related to precise estimate of safety margin (X_3), 14 related to inclusion of new projects (X_4), 13 related to lack of risk analysis (X_2), 9 related to resource leveling (X_6), and 3 related to undefined or changed scope (X_1).

It was verified statistically that the independent variable X_5 (Rework) was the only variable that affects system performance with respect to compliance with the planned time, and this became the restriction of a multiproject system. This result is related to what happened between days 20 and 40 (see Figure 5), when the inclusion of different activities to those defined for the system affect multiproject scheduling, and projects P-03 and P-04 began to fall behind, leading to rework. The control mechanism (project buffer consumption), however, allowed the realization of this effect and for actions to be taken to normalize the workload, which occurred from day 45 (see Figure 5) and was beneficial to the system.

The appropriateness of the model is assessed using two tests: the Hosmer-Lemeshow test of goodness-of-fit following criteria and Measures of Association for fit binary logistic model (Somers's D and Goodman-Kruskal Gamma). The first test assesses the model fit by comparing the observed and expected frequencies, grouping the data by their estimated probabilities, from lowest to highest; then it performs a Chi-square test to determine if the observed and expected frequencies are significantly different. The second test makes a comparison between response variable and predicted probabilities, with high values for Somers's D and Goodman-Kruskal Gamma, indicating that the model has good predictive ability.

Based on the analysis of the results provided by the software, the appropriateness can be checked as follows:

- The significance (Sig.) value of the Hosmer-Lemeshow Test is 0.401 (>0.05), which indicates that there is consistency between observed and expected frequencies: 78.9% of the pairs were concordant, whereas 18.8% of the pairs were discordant. Thus, there is almost a 50% better chance for a pair to be concordant than discordant.
- Somers's D (0.60) and Goodman-Kruskal Gamma (0.61) both have high values and are very close to one another because there are very few tied pairs. The higher the percentage of concordant pairs, the better the model performs.

With the data presented in Table 6, we intend to express the probability that the event in question (task completed in planned time) occurs as a function of influencing variables. If we try to predict the phenomenon represented by the letter y (dependent variable), and k (independent variables, $k = 7$) being represented by $X_1, X_2, X_3, \ldots,$ Xk, the general equation, or logistic function is:

$$P(y) = \frac{1}{1 + e^{(-\alpha-\beta_1 X_1-\beta_2 X_2-\beta_3 X_3-\ldots-\beta_K X_K)}} \quad (1)$$

Where $\alpha, \beta_1, \beta_2, \beta_3, \ldots, \beta k$ are the model parameters and (e) denotes the exponential function.

In Table 6, the influence variable X_5 (rework of activities) was the only one with statistical significance and, for this reason, has a value of 1.0 (1 = Yes) in Equation (2). The other influence variables (X_1, X_2, X_3, X_4, X_6, X_7) have a value of zero. The same applies to their respective parameters (βk).

From the data showed in Table 6, entering the following values $\beta_5 = -2.344$, $X_5 = 1.0$ and $\alpha = 2.242$ in Equation (2), we can calculate the probability of completing the task on time, when influence variable X_5 appears, as follows:

$$P(y) = \frac{1}{1 + e^{\left(-2.242-(-2.344).(1.0)\right)}} = 0.47 \quad (2)$$

This result indicates that when the influence variable X_5 appears, the probability of any activity of the critical chain to finish on time is 47%. For this case study, in a total of 46 activities that form the critical chain, 25 were completed within the planned time, and 21 were completed with duration longer than estimated.

Additionally, by eliminating the effect of rework, using Equation (3) to calculate the probability of the task being completed on time, entering the following values $\beta_5 = -2.344$, $X_5 = 0$ and $\alpha = 2.242$, we get the following result:

$$P(y) = \frac{1}{1 + e^{\left(-2.242-(-2.344).(0)\right)}} = 0.90 \quad (3)$$

Comparing equations (2) and (3) we can consider that the results could be an indicator that when rework (X_5) is eliminated, the probability of finishing on time is very high (90%). However, the likelihood is not 100%, which, in the case of the research data, can be an indicator to alert the system that other variables could be more relevant and become a new restriction.

Expert Judgment: Coding Interview

To explore the research questions, a focus group interview was conducted, following the guidelines of Gray (2009), with four people within the company and six people from an external company to which the case study was applied.

Project managers in the company with more than ten years' experience working on product development and with the traditional method (Critical Path) for time management were considered. External specialists were consulted because they work for a company that develops high technology products, with an environment of high uncertainty and complex projects, with experience working with the CCPM method for 20, 8, 7, 6, and 3 years, respectively.

EMBRAER, a company that is currently the third largest manufacturer of commercial aircraft in the world, is the external company that collaborated with the interviews. Since 2010, when it started applying the CCPM method to manage its portfolio of projects, they have been able to increase (39%) the number of projects delivered and reduce (21%) the average cycle time for the delivered projects (Giovanni, Cooper, & Anholon, 2017).

The methodological procedure used to codify the interviews was the theoretical coding suggested by Flick (2009), which consists of three steps: open coding, axial coding, and selective coding. The first step is to express data and phenomena in the form of concepts. In this step, texts are read, line by line, and sentences or codes are created, using gerunds to help preserve the meaning embedded in participants' responses. The second step—axial coding—refers to the enhancement and differentiation of the categories resulting from open coding, selecting those that present a greater connection between concepts to identify the relationships between codes. The last step—selective coding—enhances the development and integration of the encoding made earlier in order to obtain a central category or variable discover patterns in the data, and the conditions under which they apply.

Considering the above, we created the research questions (RQ1, RQ2) and present the results obtained for each of them in terms of open, axial, and selective coding (the coding process was carried out using NVivo 11 Pro® software):

RQ1: How is the time estimation of activities done using the CCPM method?

For project managers within the organization, the open coding for this research question included the following items (from most mentioned to the least mentioned): (1) challenging estimate of time, (2) decreasing the initial time estimation, and (3) eliminating internal security.

For external professionals, the open coding for this research question included the following items (from the most mentioned to the least mentioned): (1) decreasing the initial estimate, (2) associating the degree of uncertainty with the decrease of the estimate, (3) adjusting the initial estimate, (4) eliminating internal security, and (5) varying the percentage of decrease.

RQ2: What is the behavior of the critical resource in the multiple project environment when the CCPM method is used?

For project managers within the organization, the open coding for this research question included the following items (from most mentioned to the least mentioned): (1) Multitasking can be controlled, (2) pressing to meet the deadlines, (3) visualizing the occupation of critical resource, and (4) identifying the critical resource improves performance.

For external professionals, the open coding for this research question included the following items (from the most mentioned to the least mentioned): (1) Identifying the critical resource improves performance, (2) multitasking can be controlled, (3) defining and respecting the queue of activities prevents multitasking, (4) respecting the ability of critical resource improves performance, and (5) rescheduling of activity decreases, but is not eliminated.

Axial and Selective Coding Based on the Open Codes

Axial coding included the following categories: challenging estimate of time, decrease of the initial estimate, pressure to meet deadlines, association of the degree of uncertainty with the percentage of decrease, elimination of internal time safety, identification and critical resource protection improving system performance, and multitasking control. Selective coding has highlighted that identifying the critical resource and decreasing the initial time estimation, are the key variables.

Decreasing the initial estimate of the time of activities connects with the elimination of internal security, and this decrease depends on the degree of uncertainty or history of accomplishment of the activities. In the case of the interviewees, there is a consensus that this percentage can be between 33% and 50% for activities with great uncertainty and 0% for routine activities or for outsourced activities, with defined contractual dates. In turn, identification and protection of the critical resource connects with the fact that multitasking can be controlled and that respecting the capability of the critical resource system improves performance. In addition, identifying and protecting the critical resource connect with the fact that the rework of project activities may decrease but does not eliminate that possibility.

Relative to the pressure to meet more challenging deadlines that participants experienced, this situation was because the case study participants were not used to this new way of working; however, they felt motivated to do the job in a different way and also rewarded and satisfied with the final result. This result modifies the perception that the company has to manage projects and can affect the organizational culture in a positive way, thereby promoting a cycle of continuous improvement and the acquisition of new knowledge.

Conclusions

Based on the results and the analyses carried out, it can be argued that the limitation of projects to the critical resource in a multiproject system, as proposed by the CCPM method, allows for better distribution of the workload and facilitates the monitoring of activities and allocation of resources, when needed.

Although in the initial planning for the CCPM method the project duration increased by 35 days in relation to the traditional method, the final evaluation proved that project P-1 was executed using the same amount of time (20 days), project P-02 was executed in 65 days (17 days less) and projects P-03 (102 days), and P-04 (112 days) were executed with two more days each.

A comparison between the total time (6,572 hr) initially planned for all four projects using the traditional method, and the final time (3,632 hr) obtained by the CCPM methods, shows that a reduction of 44.7% of work was obtained.

Some authors claim that it is not clear how the CCPM method eliminates the undesirable effect of multitasking on the performance of the project schedule. In this study, logistic regression analysis showed that multitasking does not affect the performance of the system, as the effect of the critical resource (bottleneck) was protected by eliminating conflicts between resources and balancing the distribution of shared resources, as recommended by the CCPM method.

Based on the methods used, the data analyzed and the results obtained, we recommend that more practical applications be made, following the general procedure adopted for this case study, namely:

1. Field study to know the organizational culture and identify the factors that impact the estimated time of the activities, as we identified seven variables obtained from the scientific literature and the field study.
2. Evaluate the degrees of complexity and uncertainty of the project management environment to confirm if it is appropriate to use the CCPM method, in cases where they are high;
3. Scheduling and control of the project using the CCPM method, following the steps presented in Table 3;
4. Monitoring the compliance of the initially estimated terms for the activities, using a questionnaire that evaluates the presence of the independent variables defined in step (1) and use the collected data to perform a logistic regression analysis, and analyze the influence of the variables; and
5. Reviewing of the results of the project, when these are closed, by experts within the company or external to it, to make an objective evaluation of the performance of the management system of multiple projects.

There are some limitations of this research. The data were obtained from the analysis of a four-project system that shared resources in a specific company, and more studies could be done by applying the same methodology to validate the model in other contexts with more activities and projects.

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