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Comparison of PERT/CPM and CCPM Methods in Project Time Management

Taynara Takami Narita[1], São Paulo State University "Júlio de Mesquita Filho", Bauru, São Paulo, Brazil
Caio Henrique Alberconi[2], São Paulo State University "Júlio de Mesquita Filho", Bauru, São Paulo, Brazil
Fernando Bernardi de Souza[3], São Paulo State University "Júlio de Mesquita Filho", Bauru, São Paulo, Brazil
Lucas Ikeziri[4], São Paulo State University "Júlio de Mesquita Filho", Bauru, São Paulo, Brazil

RESUMO

Objetivo: Avaliar e comparar as técnicas PERT/CPM e Critical Chain Project Management (CCPM), da Theory of Constraints (TOC), em relação aos seus indicadores de estimativa de prazos de entrega e confiabilidade no cumprimento dos prazos estabelecidos.
Fundamentação teórica: A pesquisa está fundamentada na teoria de gestão do tempo estabelecida pelos métodos PERT/CPM e CCPM.
Metodologia/abordagem: Este trabalho possui um caráter experimental, utilizando-se do método de simulação computacional mediante aplicação do software Promodel. Foi modelado um ambiente fictício de projetos gerenciado pelas técnicas PERT/CPM e CCPM a fim medir avaliar e comparar seus desempenhos em termos de estimação e cumprimento de prazos de conclusão de projetos.
Resultados: Os resultados obtidos evidenciaram que o método CCPM mostrou-se mais efetivo na redução do tempo de finalização dos projetos e no cumprimento dos prazos estabelecidos, enquanto o método PERT/CPM permitiu concluir os projetos em prazos até 189% maiores do que o planejado.
Pesquisa prática e implicações sociais: Muitos gestores assumem que a melhor forma de planejar seus projetos, especialmente ao visarem prazos curtos e confiáveis, é programarem suas atividades alocando segurança em cada uma delas. Essa pesquisa reforçou a percepção já amplamente defendida pela TOC que, devido a determinados e ordinários comportamentos humanos, otimizações locais não garantem, e geralmente deterioram, bons resultados globais.
Originalidade/ valor: Existe uma carência de pesquisas que comparam as técnicas PERT/CPM e CCPM mediante modelagens e simulações computacionais de ambientes de projetos submetidos a determinados graus de incerteza, particularmente em termos das variáveis de desempenho como as aqui estudadas. Os resultados dessa pesquisa permitem, portanto, atender essa oportunidade, trazendo à luz cenários comparativos e explicações para os diferentes comportamentos observados.
Palavras-chave: Simulação Computacional; Gerenciamento de Projetos; Goldratt; Corrente Crítica; CCPM; PERT/CPM.

ABSTRACT

Purpose*: Evaluate and compare PERT/CPM and Critical Chain Project Management (CCPM) techniques, from the Theory of Constraints (TOC), in relation to indicators of delivery time estimation and reliability in meeting established deadlines.*
Theoretical framework*: The research is based on the time management theory established by the PERT/CPM and CCPM methods.*
Design/methodology/approach*: This work has an experimental character, using a method of computer simulation by applying the Promodel software. A fictitious project environment managed by PERT/CPM and CCPM techniques was modeled in order to evaluate and compare their performances in terms of estimation of, and compliance with, project completion deadlines.*
Findings*: The results obtained showed that the CCPM method proved to be more effective in reducing project completion time and meeting established deadlines. Conversely, the PERT/CPM method increased planned project completion time by 189%.*
Research, Practical & Social implications*: Many managers assume that the best approach to project planning, especially when aiming for short and reliable deadlines, is to allocate margins of safety to each scheduled activity. This research reinforced the already widely held perception of TOC that, due to certain ordinary human behaviors, local optimizations do not guarantee, and usually adversely effect, good global results.*
Originality/value*: There is a lack of research comparing PERT/CPM and CCPM techniques through modeling and computer simulations of project environments subjected to certain degrees of uncertainty, particularly in terms of performance variables such as those studied here. The results of this research, therefore, address this opportunity, bringing to light comparative scenarios and explanations for the different behaviors observed.*
Keywords*: Computational Simulation; Project Management; Goldratt; Critical Chain; CCPM; PERT/CPM.*

1. Av. Eng. Luiz Edmundo C. Coube 14-01 - Vargem Limpa - Bauru – SP, CEP 17033-360, taynara_takami@yahoo.com.br; https://orcid.org/0000-0002-4987-1240; 2. ca@caioalberconi.com; https://orcid.org/0000-0001-8252-8471; 3. fernando.bernardi@unesp.br; https://orcid.org/0000-0003-4302-7636; 4. lucas_ikeziri@outlook.com; https://orcid.org/0000-0002-3492-272X.

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1. INTRODUCTION

Project management has gained increasing importance and attention in the corporate world due to its potential to maximize profits, reduce deadlines and costs, and increase efficiency.

Considering that project management directly impacts on the achievement of desired organizational performance, interest in this process has seen a remarkable growth of 1000% over the last 15 years (HALL, 2012, p.1). This is because project management not only contributes to business development, but also offers specific techniques that favor the advancement and improvement of organizational results.

To better understand the importance of project management for the achievement of organizational results, one must understand the concept of project. Projects can be conceptualized as a non-repetitive undertaking, characterized by a logical sequence of events intended to achieve a clear and defined objective (PMI, 2017, p. 4). They are undertakings that aim to increase the ability to create value in organizations. Furthermore, projects are major vectors of change, implementating strategies and innovations that bring competitive advantage to companies, so conducting them as efficiently as possible assumes high relevance (RADUJKOVIĆ; SJEKAVICA, 2017).

However, delivering projects that meet the goals of time, cost, and quality is still a challenge to be overcome by companies (RADUJKOVIĆ; SJEKAVICA, 2017). The PMSurvey.org survey pointed out that in 59.4% of cases there is no compliance within the deadline initially set for projects (PMI, 2014). Thus, methods began to emerge to assist in the management of projects, more specifically in their time management, since, according to PMI (2017), one of the fundamental elements of every project is its temporary nature, i.e., each has a well-defined beginning and end.

As examples of techniques used in project management, there is the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT). Both have helped project managers in the planning, execution, monitoring and control of their projects, improving performance by identifying the start and finish times of each project task, establishing a flow of execution (AGYEI, 2015).

Nevertheless, in an increasingly competitive environment, with strong pressures for deadlines and limited resources, these conventional project management practices no longer seem to be sufficient (GRANER, 2014). According to Roghanian, Alipour, and Rezaei (2018), traditional tools, such as PERT/CPM, fail to overcome the uncertainty common in project environments. The authors present several examples of failures in completing projects within given deadlines, and thus the need for new project management methods arises. These failures are related to the fact that such approaches do not adequately take into account the limited availability of resources, besides the tendency to accumulate large amounts of contingency reserves in each activity, for unexpected delays (ROGHANIAN; ALIPOUR; REZAEI, 2018).

In this context, new studies and techniques began to emerge as alternative options to traditional techniques. The most recent among them, is Critical Chain Project Management (CCPM), proposed by Eliyahu Moshe Goldratt. This technique results from the Theory of Constraints (TOC) and aims to complete each project in the shortest time possible, as well as to conduct further projects without the need for additional organizational resources (HU et al., 2016).

Many are the reports of companies that have obtained performances considered quite satisfactory in the management of their schedules after employing the CCPM method, delivering their projects before the expected deadline, with a smaller budget, with the expected quality, with less stress and with a more motivated team (YANG; FU, 2014). As an example, one can highlight the use of the method by organizations such as Boeing, General Motors, General Electric, and NASA (LINHART; SKORKOVSKY, 2014).

However, little research has been identified so far that compared, through computer simulations, the CCPM and PERT/CPM techniques in terms of performance variables, such as meeting delivery deadlines in project environments subjected to certain degrees of uncertainty. According to Ikeziri et al. (2018), one of the research opportunities in the area of projects by critical chain is found in studies aimed at a better understanding of the techniques involving the CCPM method.

Furthermore, no studies have been identified that propose an evaluation, through computer simulations, of techniques recommended by CCPM, such as, for example, those that deal with the psychology of human behavior influenced by Student Syndrome and Parkinson's Law, principles that underlie the CCPM theory. This is because, according to Steyn (2000), time management techniques usually neglect the human behavior that could be expected during project planning and control. Moreover, translating human behavior into programming languages is a great challenge, since it is unpredictable.

Thus, this work aims to fill these gaps by proposing to model and simulate a single project environment managed by CCPM and PERT/CPM logics, enabling them to be compared, together with an explanation of the performance differences observed, in relation to their indicators of delivery time and reliability in meeting established deadlines. Our final intention is to answer the following research question: how do PERT/CPM and CCPM techniques behave, individually and comparatively, in terms of delivery time and on-time delivery?

2. THEORETICAL FOUNDATION

2.1 Project management

Temporality is a basic premise for project management. This does not necessarily mean that projects have a short duration, but rather that the beginning and end of their execution are well defined. The end of the project is reached when its objectives are achieved or when it becomes clear that the project objectives will not or can no longer be achieved (PMI, 2017).

According to Hall (2012), another characteristic that can be noted about projects is the existence of precedent relationships between activities. Such relationships define constraints that require that one task must be completed before the other begins.

In this context, project management can be understood as being "the application of knowledge, skills and techniques to project activities in order to meet its requirements" (PMI, 2017, p. 10). Principal among the objectives of a project is completing it on time and within budget, ensuring the scope planned (HALL, 2012).

There are ten project management knowledge areas, which are "identified areas of project management defined by their knowledge requirements and described in terms of the processes of which they comprise: practices, inputs, outputs, tools, and techniques" (PMI, 2017, p. 23). This research is limited to project time/schedule management, a knowledge area that, according to PMI (2017, p. 173), should drive the following processes:

i. Plan schedule management: the process of establishing the policies, procedures, and documentation for planning, developing, managing, executing, and controlling a project schedule;

ii. Define activities: the process of identifying and documenting the specific actions to be taken to produce project deliverables;

iii. Sequence activities: the process of identifying and documenting the connections between project activities;

iv. Estimate activity durations: the process of estimating the number of work periods that will be required to finish individual activities with the estimated resources;

v. Develop the schedule: the process of analyzing activity sequences, durations, resource requirements and schedule constraints to create the project schedule model for project execution, monitoring and control;

vi. Control the schedule: the process of monitoring the project status to update the project schedule and manage changes to the project baseline.

Within the processes mentioned, schedule development is responsible for "analyzing activity sequences, durations, resource requirements, and schedule constraints to create the schedule model for project execution, monitoring, and control" (PMI. 2017, p. 205). It is in this process that the project manager will define which technique to use, and whose choice may be decisive for the success or not of a finished project.

2.2 Project management by PERT/CPM

Within the existing techniques of project planning and control, one can mention the CPM and PERT methods. These techniques emerged in the mid-1950s and are used in project management, allowing the planning, scheduling, and coordination of activities for time and cost control (VERGARA; TEIXEIRA; YAMANARI, 2017). According to Humphreys (2014), the main objectives of the PERT/CPM tool are:

i. Minimize localized project problems;

ii. Obtain knowledge of the critical activities, whose fulfillment influences the total duration of the project;

iii. Keep management informed as to the development of each stage or activity of the project, enabling the early detection of critical factors that may hinder performance, as well as allowing for adequate decision making;

iv. Establish the date by which each activity involved should begin or complete its assignment;

v. And be a strong instrument of planning, coordination and control.

Although they were conceived at the same time and the analyses used by both are very similar, the major difference between these techniques lies in the way time is treated (AGYEI, 2015). CPM is a project management tool that aims to optimize a sequence of activities in order to ensure the completion of a project within the time expected, assuming that time estimates are deterministic and can be used to address complex scenarios (PMI, 2017, p. 210). In addition, CPM assumes that the times of activities are proportional to the amount of resources allocated to them (AGYEI, 2015).

On the other hand, PERT incorporates existing activity uncertainty times in its analyses, i.e., it considers the duration of each activity as a random variable related to some probability distribution (KARABULUT, 2017). Since its goal is to make the expected deadline for the execution of activities more feasible, the application of this technique provides the following information: the expected duration of the project and its critical path, the probability of completing the project within a given timeframe, and the probability of being completed as of a deadline (DANIELSON; KHAN, 2015).

Among the main PERT/CPM steps is the calculation of the Critical Path, which is the longest path in the network and therefore responsible for determining how long it is expected to take to complete a project. To identify the Critical Path, it is necessary to determine the duration of each path in the project, i.e. the time required to complete each path. Any delay in the critical path will delay the completion of the project and, therefore, should be prioritized so that the project is not compromised.

2.3 Project management by CCPM (Critical Chain Project Management)

Recent research and real experience suggest that there are some gaps in traditional project management methods, delay being the biggest of them (ROGHANIAN; ALIPOUR; REZAEI, 2018). To address this challenge, in 1997, Eliyahu M. Goldratt proposed an application of TOC to project management, known as Critical Chain Project Management (CCPM), which has become a new paradigm for feasible resourceful project scheduling (ZARGHAMI *et al*., 2020).

According to the Project Management Institute (PMI),

> The critical chain method is a scheduling method that allows the project team to create buffers along any schedule path to account for limited resources and project uncertainties. It builds on the critical path method approach and considers the effects of resource allocation, resource optimization, resource smoothing, and uncertainties in the duration of any critical path activity determined using the critical path method.

> To this end, the critical path method introduces the concept of buffers and buffers management (PMI, 2013, p. 178).

CCPM has a clear focus on the time management of projects, since its main premise consists of the idea that adequate time management brings benefits to the costs and scope of a project (LUIZ et al., 2019). Thus, considering that the total duration of a project is given by the sum of the set of tasks with longer duration, and that these are considered critical activities that require greater effort from project managers, CCPM aims to manage such critical activities through their effective planning and control.

The use of the CCPM technique is important because it overcomes the shortcoming of traditional project management methods, which are based on the assumption that there are unlimited resources for the execution of activities, leading to unreliable dealines as a result (ZHANG; SONG; DÍAZ, 2017). CCPM also benefits the estimation of the duration of project activities. Determining the times of each activity is a complex task due to the dependence on factors such as the availability of materials, workers, and tools, which create difficulties in predicting when such activities will be completed (ROGHANIAN; ALIPOUR; REZAEI, 2018). In this scenario, human behavior tries to compensate for these factors by adding substantial safeguards to the duration estimates of the activities, which ends up inflating the project as a whole (ZARGHAMI *et al.*, 2020).

The effect of adding security to each activity results in "[...] official estimates, those that are presented to management, twice or higher [...]" than those that are actually required for its completion (BUDD; CERENY, 2010, p.48). Furthermore, managers or coordinators at each hierarchical level within an organization often place their own securities on top of the securities constructed by the executors of activities, further increasing the duration of such activities (STEYN, 2002).

The three most common human behaviors in projects are (BUDD; CERVENY, 2010):

i. Student Syndrome: based on the human behavior of extending the due date for an activity. The feeling of having more time available to perform an activity brings peace of mind, however, the additional time is often wasted. This happens because human beings, upon noticing that they have more than enough time to perform an activity, habitually leave it until the last available minute;

ii. Turtle Operation: is the identification of human behavior that, even if the activity is finished before the deadline, does not inform its conclusion. This occurs due to two paradigms rooted in project environments: first, if the immediate superior is informed that the activity was finished before the deadline, he may be ordered to perform new activities. In other words, have even more work to do. The second paradigm is that if it is possible to finish activities ahead of schedule as planned in the project, this anticipation may be taken into account in future estimates. So, in order to maintain their reputation and comfort, human beings neglect the fact that an activity has been finished before its deadline;

iii. Parkinson's Law: this behavior adds to the turtle effect, giving the false impression to a performer that an activity needs to be improved/slowed down. Parkinson's Law states that the work is extended to fill all the available time, that is, even if the activity is finished before the deadline, human beings tend to review its execution and try to improve some aspect of the activity. Thus, not infrequently, modifications are made to activities that fall outside the scope of the project and bring no benefit to it. The only result is the consumption of the execution time of an activity, which could have been delivered before the deadline.

In order to absorb project safeguards and provide more reliable deadlines, CCPM introduces the lung concept, i.e. buffers. Goldratt (1997) proposed, through the buffer concept, to take half of the average estimated time for each activity, i.e. remove the safeguards from the individual tasks, and transfer half of the local safeguards to the end of a project chain in the Project Lung, thus protecting its completion (IKEZIRI et al., 2018).

As mentioned above, the goal of buffer management is to reduce the safety times required in activities, adding the final safety of the activity chains and thus providing the means for a new system of monitoring and control of the project, based on buffer utilization levels (GHAFFARI; EMSLEY, 2015). According to Steyn (2002), there are three types of buffers in a project: Project Buffer, Feed Buffer, and Resource Buffer.

It can be concluded, therefore, that by using the CCPM method to schedule a project, unnecessary activity safety times can be eliminated and buffers used as a mechanism to decrease project risks, ensuring that a given project is executed more successfully with respect to meeting its deadline (MA; HU; DENG, 2019).

3. METHODOLOGICAL PROCEDURES

3.1 Object of study

The methodological importance of a research study is justified by the need for an adequate scientific basis. Thus, given the experimental nature of the work in question, the computational simulation method was used, which is a tool capable of representing a model and evaluating it numerically (SUZEK; BING, 2020). Corroborating this, Suzek and Bing (2020) state that the goal of computational simulation is to evaluate the behavior of real systems under various conditions.

According to Banks *et al*. (2004), a simulation model, once developed and validated, is capable of investigating a wide variety of "what if" questions about real systems. Thus, the method employed in this research - computer simulation - provided the modeling for the project networks based on PERT/CPM and CCPM methods and the combinations of scenarios performed, by which means the measurement of their performance through previously defined indicators could be achieved.

After defining the research method, the next step was to choose the simulation software for building the models. The software chosen was ProModel, which is widely used to plan, design, and improve new or existing systems and processes, due to its design and user-friendly interface that provides fast and reliable simulations (CHEN; LI; GAO, 2015). Moreover, according to ProModel Corporation (2015), it is capable of running experiments with large numbers of replications quickly, and has several options for result analysis.

3.2 Data collection and analysis procedures

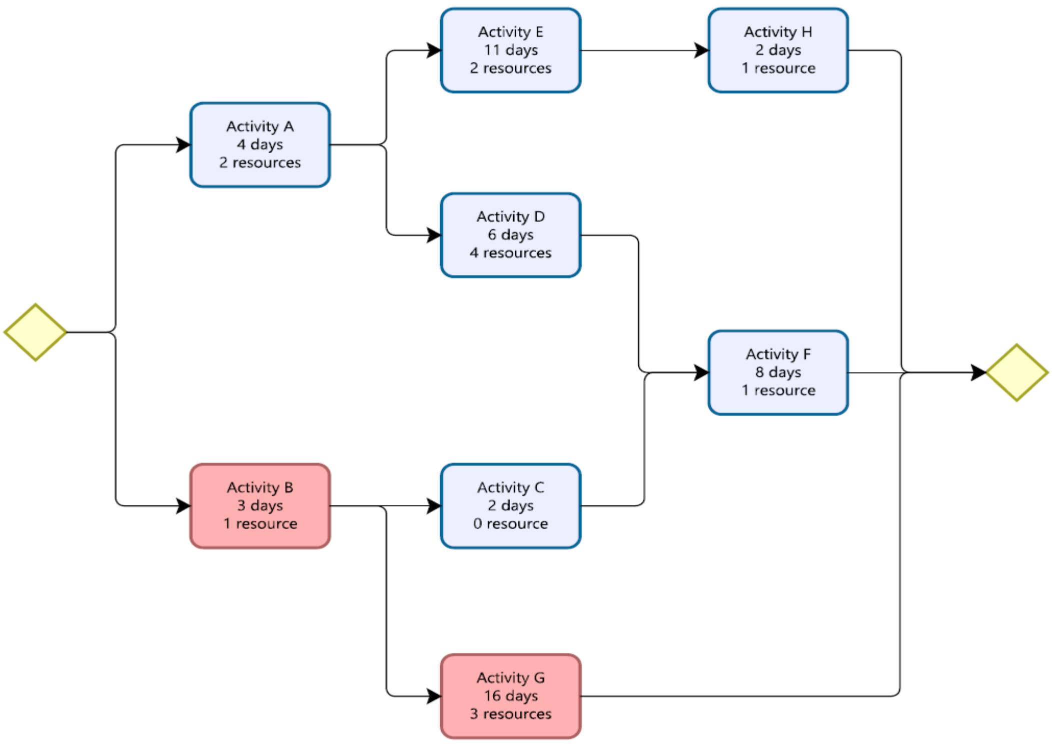
The model built to conduct this research needed to offer a project environment that allowed for pertinent analysis and comparison between the PERT/CPM and CCPM techniques. For this reason, the project network proposed in Wei, Liu, and Tsai (2001) was selected. In addition, the research was based on Harrell, Ghosh, and Bowden (2000), who discuss simulation with an emphasis on the ProModel software. The steps followed by the research were:

Step 1 – Problem Definition: how do PERT/CPM and CCPM techniques perform comparatively in terms of delivery time commitments and meeting delivery deadlines?

Step 2 – Definition of the objectives: the objectives are (i) to compare the techniques by modeling and (ii) simulate a problem extracted from the literature;

Step 3 - Formulation and planning of the model: Following the analysis of a number of projects explored in scientific articles, we selected one that provided a convenient analysis and comparison between PERT/CPM and CPPM techniques, including the presence of resource constraints. To this end, the project network proposed in Wei, Liu and Tsai (2001) was selected, as shown in Figure 1.

Figure 1 - PERT/CPM Network.



Source: Adapted from Wei, Liu, and Tsai (2001).

According to the problem provided by Wei, Liu and Tsai (2001), there are four resources available to do activities A, B, C, D, E, F, G and H. Respectively, according to Figure 1, each activity needs the following number of resources for its execution (2, 1, 0, 4, 2, 1 3, 1), and activities in parallel can be scheduled as long as the sum of the resources needed for their execution is less than 4. To calculate the Critical Path, such capacity constraints (conflicts in the use of resources) were ignored.

After defining the project network to be used, the next step was to transform the PERT/CPM and CPPM concepts into logical structures, adopting the following premises in order to differentiate and model them according to human behavior:

i. The activity times follow a right-symmetric triangular distribution;

ii. Initial durations of the problem activities refer to an 80% probability of success;

iii. Average value (50% of the area under the triangle) is equal to half of the value initially established by the problem (commitment initially established by the person in charge of the activity);

iv. In the PERT/CPM model, start and end dates must be established for each activity, with the activity not starting before the established start date (even if the previous activity has already been completed). There is no incentive to start the subsequent activity earlier, since it is highly certain to be completed on time;

v. In the PERT/CPM model, activities never finish before their end date, due to the behaviors of Operation Turtle and Parkison's Law. If during the simulation run the activity ends before its end date, it is assumed that the activity ended on the initially established end date;

vi. In the PERT/CPM model, due to Student Syndrome, activities are started only when there is a 50% probability of on-time completion remaining;

vii. In the PERT/CPM model, therefore, no activity starts before its scheduled date, but it can start after;

viii. In the CCPM model, the relay race rule applies: as soon as the previous one is finished, the next one starts;

ix. In CCPM, only the start dates of each activity branch should be scheduled, considering the absence of resource conflicts, activities with durations equivalent to a 50% probability of completion within the established start time, and buffers equal to 50% of the total branch time.

Step 4 - Development of the computational model: In this step, the conceptual model was translated through the use of entities, locations, and other tools. In other words, the previous rules were modeled in the ProModel software;

Step 5 - Model validation: The networks were initially modeled with deterministic times and their values were compared with the theoretical solutions of the PERT/CPM and CCPM techniques *(Step 3)*;

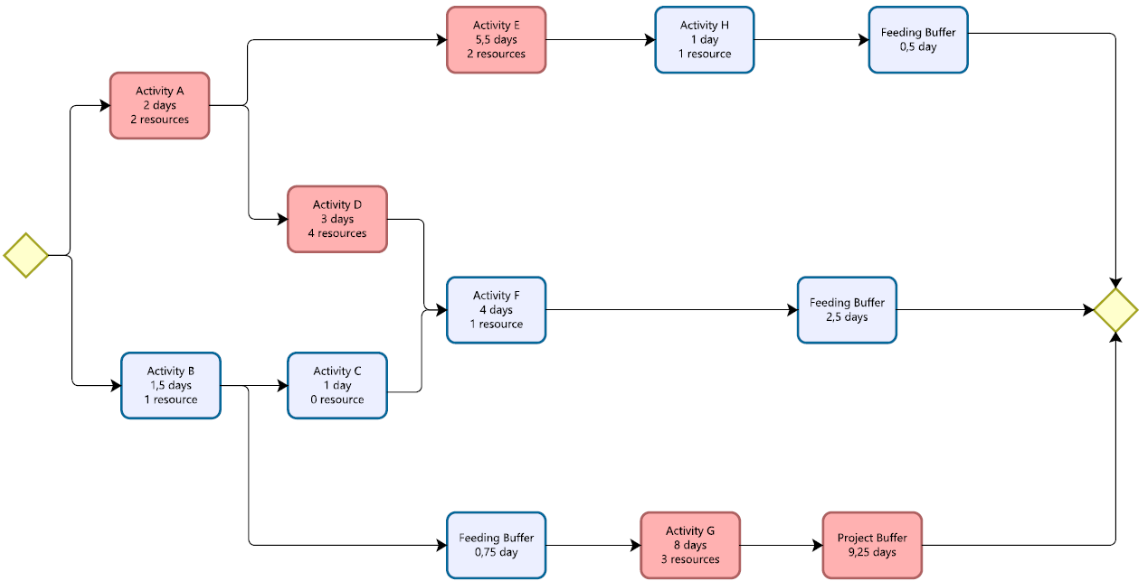
Step 6 - Simulation planning and execution of the experiments: Each model was replicated 100 times and then reports were extracted with the final duration/completion times for each activity and, consequently, for the completion of the project as a whole.

Step 7 - Analysis of the results: The initial analysis focused on comparing the completion times, for both the PERT/CPM and CCPM models, of the activities and the project with the initially calculated times, in order to identify whether or not the initially established deadline was met.

4. RESULTS

The longest paths of the project were initially identified, that is, the Critical Path, since these represent its delivery time. Thus, it can be said that the Critical Path (as recommended by the PERT/CPM method) and, later, the Critical Chain (according to the CCPM method) were identified. For the determination of the Critical Chain, the construction of the project network by this method was also necessary, since without its construction it would be impossible to determine. The project network, by the CCPM method, is defined in Figure 2.

Figure 2 - CCPM network.



Source: The authors.

The Critical Path of the project is composed of the sequence BG, since these are the activities that have the longest path (in days) to the project's conclusion. Therefore, it can be seen that the project will be completed in 19 days. On the other hand, for the Critical Chain - the longest path of the project with the deconflict of resources and eliminating the safeguards of each activity - a new sequence of activities was identified (ADEG), with a duration of 18.5

days (37 days divided by 2), respecting the premise that there are four resources available for the execution of the activities. A final project buffer was also established, the duration of which equals half of the sum of the eliminated activity durations, i.e., 9.25 days (half of 18.5 days). In this context, the shortest safely achievable time frame is 27.75 days.

The first analysis compared the initially promised project completion times, which are 19 days according to the PERT/CPM method and 27.75 days according to the CCPM method. It can be verified, even before the simulation, that the PERT/CPM network will present a delay in the conclusion of the project due to both the unavailability and conflict of resources, because activities D, E and G are scheduled to be performed in parallel. However, the execution of these activites demands more than the four available resources. Thus, the completion of one activity means that the others would have to wait, that is, they would be executed in sequence and not in parallel. Considering that, by definition, the PERT/CPM method must prioritize the activities of the longest path, in this case, the Critical Path (BG activities), it was computationally modeled that, whenever faced with a conflict in the use of resources, the activities of the Critical Path would be given preference.

As a consequence, after 100 replications, and considering the rules or assumptions assumed in Step 3 of the research method, it can be seen that the PERT/CPM method cannot meet the 19-day deadline, as shown in Table 1.

Table 1 - Comparison of project completion times

	PERT/CPM	CCPM
Estimated deadline (days)	19	27,75
Best scenario (days)	45	27
Worst scenario (days)	55	31
Replication averages (days)	48,58	27,93
Deadline achieved (%)	0	57

Source: The authors.

The average result of the replications, for the PERT/CPM network, is that the project is completed in 48.58 days, a 155.68% longer time period than initially planned. Even in an optimistic scenario of replications, where the observed total duration of the project was the shortest (45 days), there is a delay of more than 130% when compared to plan. Therefore, it can be seen that despite initially offering a shorter and theoretically more attractive project completion time, in projects managed by the PERT/CPM method there is no compliance with the established schedule plan.

On the other hand, the CCPM method performed better, with 57% of the rounds finished in 27.75 days or less. It can be said that since the Critical Stream has only four activities, the effect of statistical aggregation on the project buffer is small, which justifies the delay of 43 projects. If, aware of this, the manager had opted for a more conservative project buffer, such as, for example, 70% of the total duration of the Critical Chain activities, a deadline of 31.45 days would have been promised, with 100% compliance with this deadline, according to simulated data.

It can also be observed that even in the best case scenario of PERT/CPM, where the minimum value was 45 days of duration, this is still 45% worse than the worst result of the CCPM scenario. We conclude then, that the use of the CCPM method technique is more efficient regarding the possibility of meeting the established deadline.

Tables 2 and 3 present the results concerning the waiting and operation (execution) of the activities managed by the PERT/CPM and CCPM methods. By observing Table 2, it can be seen that in some project activities, such as activities D and H, more time was wasted waiting for the activity to start than with its execution. Taking activity H as an example, it can be observed that from the scheduled activity start date until its conclusion, only 9.67% of the time was spent with its execution, and 90.33% of the time was wasted waiting for the execution to begin.

Meanwhile, the data presented in Table 3 demonstrate that the scheduling of activities, according to CCPM assumptions, such as the elimination of resource conflict in conjunction with respect for technological precedence, contributes to the timely completion of the project.

Table 2 - Average of the state of activities in the PERT/CPM network

	Waiting (%)	Operation (%)
Activity A	0,00	100,00
Activity B	0,00	100,00
Activity C	22,97	77,03
Activity D	83,31	16,69
Activity E	61,25	38,75
Activity F	78,00	22,00
Activity G	9,36	90,64
Activity H	90,33	9,67

Source: The authors.

Table 3 - Average of the state of activities in the CCPM network

	Waiting (%)	Operation (%)
Activity A	0,00	100,00
Activity B	0,25	97,02
Activity C	0,00	100,00
Activity D	0,00	100,00
Activity E	0,00	100,00
Activity F	0,00	100,00
Activity G	0,95	99,05
Activity H	0,72	99,28

Source: The authors.

The activities must also be analyzed individually in order to verify the impact of human behavior on the time of each of them. From the data presented in Table 4, one can verify the negative impacts of the human behaviors studied on the duration of each of the activities managed in the PERT/CPM scenario, making them, on average, 84.06% longer when compared to the CCPM scenario. Therefore, it can be stated that taking into account such behaviors seems to be essential for a project's success.

Table 4 – Comparison of the average operation times of the project activities (in days)

	PERT/CPM	CCPM
Activity A	4,74	2,66
Activity B	3,78	2,28
Activity C	2,35	1,66
Activity D	6,06	3,76
Activity E	11,63	6,01
Activity F	8,46	4,71
Activity G	17,59	8,45
Activity H	2,69	1,60

Source: The authors.

5. DISCUSSIONS

The central theme of this research is the analysis of the behavior of PERT/CPM and CCPM techniques, individually and comparatively, in project schedule management, taking into account the performance variables and compliance with the project deadlines. From a computational model built in the ProModel software, a project network based on the fictitious scenario of Wei, Liu, and Tsai (2001) could be modeled. With the model built, simulation experiments were performed with various scenarios to analyze and compare the calculations of the estimated completion times and the actual project completion times.

The data obtained from the computer simulations indicate that the use of Critical Chain can provide significantly superior results to the classical forms of time management based on the PERT/CPM methods. Indeed, the comparison reveals that the CCPM method provides more reliable completion times (57% on-time completions), while the PERT/CPM method did not meet the deadline in any of the replications. These results are in line with Kendall (2005), according to whom CCPM actually represents a paradigm shift for an organization's top management, generating results that are 50 to 100% better than traditional methods in terms of time, budget, and scope.

This performance difference can be justified by the responses to undesirable effects arising from human behavior allowed by the CCPM method, such as, for example, removing the individual safeguards allocated to the activities and aggregating them at the end of the project (project buffer). In this way, CCPM manages to protect the project against time variations and proactively manages task completion (WATSON; BLACKSTONE; GARDINER, 2007).

Another factor that justifies such a performance difference is the scheduling of activities and calculation of a project's longest path (Critical Chain), taking into account the deconflict in the use of resources. These factors help explain the superiority observed in the CCPM method, because even in its worst case scenario (project completed in 31 days) it still obtained a better result in terms of meeting the stipulated deadlines than the PERT/CPM method in its best performance scenario (project completed in 45 days).

This last consideration is one of the major differences between CCPM and the traditional methods used by organizations to manage their schedules, which generally take into account only the precedence of activities in determining the total duration of a project, ignoring the fact of who (resource) will perform such activities. Conversely, CCPM defines the longest path as the set of tasks that determines the total project duration, taking precedence and resource dependencies into account and protecting it with buffers located at the end of that path (GOLDRATT, 1997; LUIZ *et al.*, 2019).

6. CONCLUSION

Based on the analyses performed, it can be concluded that, within its methodological and scope limitations, the objective of the work was achieved. After comparing the performance of the PERT/CPM and CCPM methods through computer simulation, it was observed that the CCPM method presents a better performance, showing itself to be more effective in reducing project completion time and meeting stipulated deadlines.

Despite initially reporting a longer delivery time, CCPM proved to be more effective in the way it allocates resources and manages schedules, since it estimates a more assertive date for project completion. After all, there is no benefit in offering shorter delivery times, as in the case of traditional methods, if such deadlines are not met or become impractical, thus resulting in potential contractual fines and negative impacts on the image and competitiveness of the organizations that practice them.

From the study performed, it was possible to conceptually confront the PERT/CPM and CCPM techniques and thus better understand the reasons why CCPM has greater effectiveness with respect to project completion times. In addition, the models and computer simulations enabled us to analyze the differences in performance of both techniques in project environments subject to certain degrees of uncertainty, serving as teaching material and support for classes that address topics such as project management and time or schedule management techniques.

Finally, it is important to emphasize that this research was limited to analyzing a single, small activity network model. Future work could be conducted taking into consideration larger networks and/or other resource availability scenarios, as well as a more in-depth study, in order to understand the impacts of individual human behaviors on project performance.

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