T.C.

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INSTITUTE OF GRADUATE STUDIES

ALTERNATIVE BUFFER SIZING APPROACHES FOR CCPM_

A CASE STUDY IN PALESTINE

Masters of Applied Science Thesis

Mohammad Hasan Jaber

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Department: Industrial Engineering

Program: Engineering Management

Supervisor: Assist. Prof. Dr. Zeynep Gergin

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Date 24.05.2024

Mohammad Jaber

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Programı	**: Mühendislik Yönetimi**
Tez Danışmanı	**: Dr. Öğretim Üyesi Zeynep GERGİN**
Tez Türü ve Tarihi	**: Yüksek Lisans – Haziran 2024**

ÖZET

KZPY'de Alternatif Tampon Boyutlandırma Yaklaşımları: Filistin'de Bir Vaka Çalışması

Mohammad Jaber

Gün geçtikçe daha karmaşıklaşan ve küresel bağlantılı bir dünyada başarıya ulaşmak için Proje Yönetimi metodolojilerinin uygulanması çok önemlidir. Kritik Yol Metodu (CPM), 1997'de Kritik Zincir Proje Yönetimi (KZPY) tanıtılana kadar yaygın olarak kullanılan proje çizelgeleme yöntemi olmuştur. CPM uygulamalarının yaygınlığı hala baskın olarak görülmekle beraber, özellikle kaynak kısıtlı projelerin zaman yönetiminde KZPY'nin de adapte edilmesi sürmektedir. Diğer yandan, KZPY yaklaşımı ile tanıtılan en uygun tampon boyutunu bulmak hala büyük bir zorluktur ve bu alandaki çalışmalar oldukça sınırlıdır. Bu motivasyonla, bu tez çalışması, kaynak yoğun bir alışveriş merkezi projesi örneğine KZPY ilkelerinin uygulanmasını incelemek amacıyla başlatılmıştır. Ayrıca, Kareler Toplamının Kare Kökü (SSQ), Yoğunluk Uyarlamalı Prosedür (APD), Kaynak Yoğunluğu Uyarlamalı Prosedür (APRT) ve Göreceli Dağılım (RD) gibi literatürde önerilmiş dört farklı tampon boyutlandırma yaklaşımı incelenmiş ve performansları seçilen vakaya uygunluk bağlamında için karşılaştırılmıştır. Sonuçlar, En iyi proje tampon büyüklüğüne APD yöntemi uygulanarak ulaşıldığı gösterilmiştir.; projeyi tamamlama süresi 555 gün olarak hesaplanmış olup, CPM yaklaşımına(dengelenmiş kaynaklarla) göre 114 gün (17%) daha kısadır. Çalışma ve bulgular, proje özelliklerini dikkate alarak uygun tampon boyutunun benimsenmesinin KZPY uygulamalarını iyileştirmek için önemini vurgulamaktadır.

Anahtar Kelimeler: Kritik Zincir Proje Yönetimi, Proje Yönetimi, Proje Tampon Boyutu.

University	**: İstanbul Kültür University**
Instittute	**: Institute of Graduate Studies**
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ABSTRACT

The implementation of project management methodologies is pivotal in achieving success in an increasingly complex and globally connected world. The widely used project scheduling method have been the Critical Path Method (CPM) until Critical Chain Project Management (CCPM) is introduced in 1997. Although CPM still dominates the scheduling approach in practice, CCPM is also continuously adopted to scheduling management of especially for resource constrained projects. On the other hand, finding the optimum buffer size introduced in CCPM approach is still a big challenge and studies on this area are still quite scarce. With this motivation, this thesis study is initiated to explore the adoption of CCPM principles to a resource-intensive mall project case in Palestine. Moreover, four different buffer sizing approaches proposed in the literature such as; Square Root of Sum of the Squares (SSQ), Adaptive Procedure with Density (APD), Adaptive Procedure with Resource Tightness (APRT) and Relative dispersion (RD) are studied and their performance are compared for their applicability for the selected case. The results revealed that the best option for project buffer size is obtained by applying APD Method; the duration to complete the project is computed as 555 which is 114 days (17%) less than CPM approach (with leveled resources). The study and the findings, underscores the importance of adopting appropriate buffer size considering the project characteristics in order to improve CCPM practices.

Keywords: Critical Chain Project Management, Project Management, Project Buffer Size

1. INTRODUCTION

One of the most important goals of the critical chain is to improve the performance of tasks in the project by controlling the resources in the project and overcoming the problems facing the project such as time and available budget.

In the field of project management, finding new and improved methods on every project is essential to navigating the complexity of contemporary projects. A strong project management strategy is more important nowadays in Palestine, a country with its own set of opportunities and problems. This thesis delves into the application and implications of Critical Chain Project Management (CCPM) in the Palestinian landscape.

Palestine's unique physical, political, and cultural characteristics create a unique setting for project implementation. The region has a great deal of potential for growth and development because of its resilient past. Conventional project management techniques, however, may not be enough for dealing with the particular difficulties found in this scenario. As a result, investigating cutting-edge approaches like critical chain project management becomes essential as well as useful.

Over time, project management has changed as a discipline in response to the changing character of global environments and industries. Within this continuum, CCPM stands out as a paradigm change that challenges traditional approaches by strategically emphasizing resource management and project limits. In light of this, the aim of this thesis is to analyze the basic ideas of critical chain project management, apply them to a completed project located in the State of Palestine, draw conclusions from this project, and find out the efficiency of critical chain project management. By focusing on the particular difficulties present in the region, it can be seen whether CCPM may serve as a catalyst to overcome challenges, make optimal use of available resources, and ultimately contribute to seeing projects through to completion in Palestine.

In the following chapters, the transition extends from discussing the theoretical foundations of CCPM to exploring its actual implementation in a resource-intensive mall project in Palestine. Moreover, finding the optimum buffer size introduced in CCPM approach is still a big challenge and studies on this area are still quite scarce. With this motivation, also explore the adoption of four alternative buffer sizing approaches. The findings explored from this research would contribute to the academic conversation about project management while providing useful suggestions for project managers working in the Palestinian context.

For this reason, this thesis compares and contrasts CPM and CCPM project scheduling techniques, highlighting the benefits and drawbacks of each approach for resource-dependent projects. It displays the additional features that may be attained using CCPM along with the reasons for its application. In order to show how much CCPM may be more dependable and effective in terms of saving time and achieving the goals of this type of project, the research also provides an example of how both strategies are applied in a real case study.

It is difficult to choose between using the CPM or CCPM approach for project planning since the case study this thesis examines is a resource-dependent project. Because there isn't much previous research comparing the two approaches, this study aims to shed light on the benefits and drawbacks for each of them when it comes to managing and organizing projects of this nature. Through a comparison of the two approaches and the presentation of the numerical findings obtained from applying each to a real-world case study, this research will contribute to the area of project management both academically and practically.

In this research, a detailed explanation of both CPM and CCPM provided, and a comparison between them made by applying the principles of each theory to a commercial project in the State of Palestine as a real study. To achieve the research objectives, the thesis has been divided into six sections; following this ‘Introduction’, ‘Literature Review’ provides the research on existing literature on project management methodologies, with a specific focus on CCPM and CPM, establishing the theoretical framework for the study. ‘Methodology’ section outlines the flow of the methodology and explains the formulation of the techniques to process CCPM and alternative buffer sizing approaches such as Square Root of Sum of the Squares (SSQ), Adaptive Procedure with Density (APD), Adaptive Procedure with Resource Tightness (APRT) and Relative dispersion (RD). These are implemented for a real-life case project and the results are discussed under the ‘Implementation’ section of the thesis. Finally, in the ‘Conclusion’ the main findings are summarized and the results are concluded in the unique context of the Palestinian project studied together with the insights for future research.

2. GENERAL INFORMATION

2.1. Project Management

Project management is methodical planning, carrying out, and supervising of a project from beginning to completion. To accomplish particular goals within a given schedule and budget, it entails setting project goals, obtaining necessary resources, and organizing team efforts. Project scope, time, cost, quality, stakeholder management, communication, and risk are all important components (Pedrini & Ferri, 2019).

The phases of the project management life cycle, which include planning, initiation, execution, monitoring and controlling, and closing, are often followed. The goal and viability of the project are evaluated at the outset. Planning entails laying out a thorough schedule, establishing goals, and assigning resources. The project plan is put into action and tasks are completed during the execution phase. Controlling and monitoring make sure the project stays on course and that necessary corrections are made. At last, the closing phase entails finishing all project-related tasks, getting approval from clients or stakeholders, and recording lessons learned (Keshta, 2022).

Resource management in projects is considered one of the most important things to focus on, as it represents multi-faceted challenges. One of the most important challenges is providing and allocating available resources for tasks and projects. Sometimes projects are delayed, the necessary resources are lacking, and they are not provided in the necessary time. These are among the most common problems that cause disruption to plans. Issues include unexpected and drastic changes in the scope of the project or unexpected constraints on available resources. The difficulty of estimating resource needs in projects leads to a lack of careful use of resources. In order to address the challenges represented by resources, rapid methodologies and tools must be adopted to allocate resources in projects to ensure that projects progress and do not delay the deadline within the constraints of available resources (Muntu, 2021).

2.2. Critical Path Method (CPM)

The critical path method is a project management method that determines the sequence of tasks without any delay, which means that any delay in these tasks will directly affect the project schedule. By examining task dependencies, it creates a critical path and determines the earliest and latest start and finish times for every task. Across the use of the longest path across the project, CPM helps project managers to organize tasks into priority lists, distribute resources effectively, and achieve project completion on schedule.

2.3. Critical Chain Project Management (CCPM)

Critical chain project management (CCPM) emerged through the theory of constraints (TOC) developed by Eliyahu M. Goldratt through his research and books. He initially focused on manufacturing processes and then used project management in his concepts. The idea behind CCPM is to identify and manage the critical chain of tasks within a project, which is the longest sequence of dependent tasks that determines the project's duration. CCPM emphasizes the importance of protecting the critical chain from delays by adding buffers, such as project buffers and feeding buffers, to account for uncertainties and variability. One of the key differences between CCPM and traditional project management approaches is the removal of individual task-level buffers, instead consolidating them into project-level buffers. This approach aims to optimize resource utilization and improve project completion times (Goldratt, 2016).

2.3.1. Critical Chain Keys

The critical chain is represented by three main headings as described below:

1. Project Network: In the critical chain, it starts from the last task of the project and then works backward, which helps to know the resources and determine the next steps to achieve the most efficient result without experiencing any problems.
2. Resource Availability: One of the most important features of the critical chain is that it takes resources into account, unlike other methods. These resources include materials, people, equipment, and anything required to complete the project. The critical chain is at all stages of the project. When the need for any project resource appears, it is provided directly through the buffers in the project.

3. Task Duration: The time required to complete the task is determined by the planners present in the project, the duration is determined for the activity time only without adding a buffer time or safety to the activity. The buffer time is added only in the case of the project level or that depends on the main project flow, the project buffer is distributed to all activities, not to specific activities or tasks.

2.3.2. CCPM Buffer Types

As mentioned earlier, critical chain management focuses on the buffers available in the project, some of which add time to the project and some that do not (Eby, 2022).

1. Resources Buffers: Planning for the resources in the project and keeping them from running out, and when additional resources are needed, resource buffers alert the project owners. The resource buffers are included in the project planning by the project planners before they are needed. Resources buffers do not add time to the project.

2. Project Buffer: The project buffer for the project is after the completion of all project activities and before the completion date. All projects contain one project buffer that is approximately half of the estimated duration of the project.

3. Feeding buffers: It is the time that is added to the end of the sequence of non-critical activities, before joining with the critical chain, and is estimated to be half the expected duration of the relevant activities sequence. Figure 2-1 explain the Buffer types for CCPM And how it affects the project.

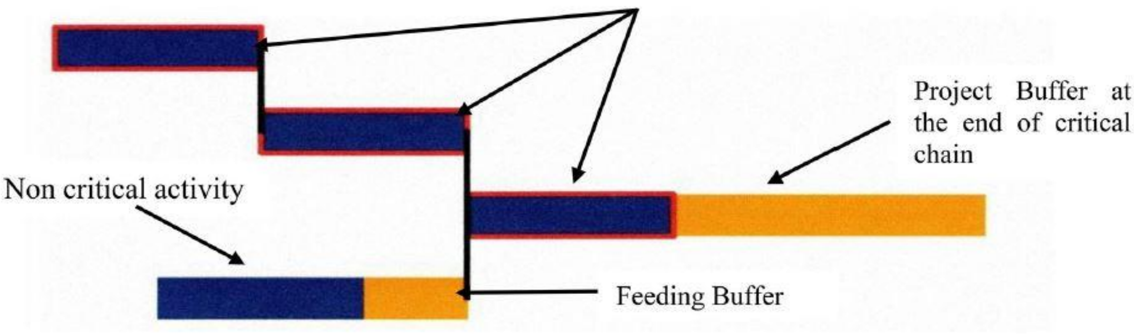

Figure 0-1. Project – feeding buffer.

2.3.3. Benefits of CCPM

A research proposes that CCPM teachings encourage more selfless collaboration in project organizations, which results in revived employee enthusiasm, improved teamwork, and a greater sense of joy in work (Li, Ma, & Wang, 2014). Another also agrees on the contributions and innovations of the methodology and reports the cultural shift resulting from the removal of important individual responsibilities and the promotion of team work with time estimates as boundaries and shared buffers. (Ghaffari & Emsley, 2017)

According to Trojanowska and Dostatni, the method works to contribute to increasing the impact of project management education for students, regardless of the lack of scientific evidence reviewed by the researchers in the effectiveness of controlling the critical chain project (Trojanowska & Dostatni, 2017) .

Another study state that workload distribution and monitoring and resource allocation skills are increased as a result of the application of the CCPM approach, which restricts projects to the critical resource in a multi project system. The final review revealed that, despite an initial increase in project duration, the CCPM method allowed projects to be completed in the same amount of time or less than the previous way (Ordon˜ez, 2019). Wei-Xin and Long (2014) also claimed when comparing the final time gained by CCPM to the initial planned time using the traditional method, the adoption of CCPM resulted in a considerable reduction of 44.7% in overall effort. The CCPM method was used to address the negative impact of multitasking on project schedule performance. It successfully reduced resource conflicts and balanced the distribution of shared resources (Wei-Xin & Long, 2014).

Numerous benefits of CCPM are identified through the research are summarized as follows:

• **Improved resource utilization**: Developing and improving the resource utilization process by controlling the resources in the project, according to the critical chain. It provides resources when needed, reduces the number of resources, and reduces unnecessary time in the project (PMI, 2017) (Agarwal, Mukesh Gupta, Kumar, & Luhach, 2015) .

• **Reduced project duration**: Reducing the duration of the project through effective and successful management of the critical chain and the application of all its steps, the critical chain can reduce by 25 percent of the project duration (Steyn, 2001) (zohrehvandi, khalilzade, amiri, & shadrokh, 2020) .

• **Increased project predictability**: CCPM works on risk management by knowing the critical paths and providing safety buffers, by identifying potential project delays and managing risks before they occur so that CCPM can predict the future (Bevilacqua, Ciarapica, & Giacchetta, 2009).

• **Better project outcomes:** CCPM provides a scientific and effective approach to managing complex projects that are subject to resource and time constraints and uncertainty. It improves project performance, reduces project time, and improves timely completion of tasks (Shanlin & Fu, 2014).

• **Enhanced team communication**: CCPM requires cooperation between the components of the project, including engineers, managers, and workers, to reach the best result in terms of buffers and time for the project (Bevilacqua, Ciarapica, & Giacchetta, 2009) .

2.3.4. Weakness of CCPM

On the other hand, some weakness of CCPM are also identified through the research and summarized as follows:

• **Difficulty in accurately estimating task duration**: CCPM depends on completing the tasks in a shorter time. It may be difficult to determine the necessary time needed for each task if the buffers and potential delays for the tasks are not taken into account (Li, Ma, & Wang, 2014).

• **Need for specialized software**: CCPM needs specialized programs in management, implementation, and protection from project variables. These programs may cause cost to project owners if they do not have access to these programs (P.Leach, 2014). Microsoft Project is widely used as a project management tool to monitor the progress of the project despite the lack of specialized simulation software, Features in Microsoft Project like Tracking Gantt, Report in Progress, and resource overview help the project manager manage the project (Aziz, 2014).

• **Dependency on team communication and collaboration**: One of the advantages of CCPM is that it relies heavily on the cooperation of the team, which can lead to problems in the event of communication failures or problems between the team and lead to project delays and non-completion of tasks (Roghanian, Alipour , & Rezaei, 2017).

• **Buffer sizing challenges**: One of the challenges facing CCPM is determining the size of the buffers for the project. If the buffer is too small, it may not provide protection against diversity in the duration of the task or uncertainty, and if the buffers is too large, it may lead to delays in the project (Peng & long, 2022) (Ma, hao, xiao, & Zho, 2019) . Abidah and Al Hazza studied the critical chain technique with an emphasis on buffer management and analyzed comparisons between several buffer sizing techniques to choose the right buffer size for the schedule (Abidah & Al Hazza, 2021).

• Resource contention issues: If there is more than one project under implementation and they share the same resources, it may lead to conflicts in obtaining these resources to complete their tasks in each project, which will lead to delays in completing the tasks and thus completing the project (Peng & long, 2022) (Ansari, Khalilzadeh , & Hosseini , 2022).

Table 2.1 provides a concise overview of the distinctions between CPM and CCPM across various critical aspects of project management.

Table 2.1. Differences between CCPM and CPM

Critical Path Method	Proposed CCPM solution
Safety time is imbedded in individual tasks	Reduce task time estimates, allow for project and feeding buffers, do away with intermediate milestone responsibility, and modify the culture associated with activity time estimation.
Parkinson's Law causes delays in projects	Move safety time from individual activities to project and feeding buffers.
Parallel activities do not receive sufficient recognition.	Insert feeding buffers where noncritical sequences join critical chain.
There is an early vs. late start dilemma	Let feeding buffers dictate noncritical activities' start times.
Resource constraints occur across multiple projects	Recognize the resource(s) that is the critical chain
Multitasking happens	Avoid multitasking
Managers focus on cost	Focus on time
Projects finish late	All of the above

3. LITERATURE REVIEW

This section provides studies on CCPM in the literature for the last 20 years. CCPM has been applied in various projects from different sectors, all reporting the benefits gained.

A study was conducted by Sarkar, Shraddha and Jha (2021) aimed at developing an improved work for managing the critical project chain dealing with highway projects in the state of India by using CCPM with the theory of constraints (TOC), a philosophy that is used to develop management techniques. The results showed that the use of this theory leads to generate buffers with suitable sizes and enough robustness to conduct the currently used buffer sizing procedures.

One of the most important problems facing construction projects is the constraints and lack of management, which leads to delays in the completion of the project because of the lack of enter to the necessary resources for the project. A study was conducted aiming to increase quality and reduce project time by linking the CCPM method with resource constraints for scheduling construction projects. In this method, each activity is carried out intermittently due to uncertainty, the duration of the activity is fuzzy numbers with triple intervals, and then analyzes of these results and work to solve them through equivalent models (Dalouchei, Mousavi, Antucheviciene, & Minaei, 2022).

CCPM was applied in the field of the automotive industry in the field of research and development (R&D), in addition to the logic of evidence (LOE) based on the priority of the task. This method consists of an organizational model, decision, and axioms. Study by Yang and Fu (2014) applied this case to a research and development process for a car company in China. The results proved that this method is good by finding solutions to the problem of material conflict with the existence of multiple projects, which is better than CCPM based on the priority of the project. Figure 3-1 shows the decision model of multi-project resources-based constrained scheduling. CCPM and buffer sizing were applied to the construction of railways in the metro, with reference to the result of the simulation analysis RESM gives the maximum limit of the buffer size, but the C&P method gives the minimum limit of the buffer size. The implementation of CCPM reduced the project time by 3% (Ansari, Khalilzadeh , & Hosseini , 2022).

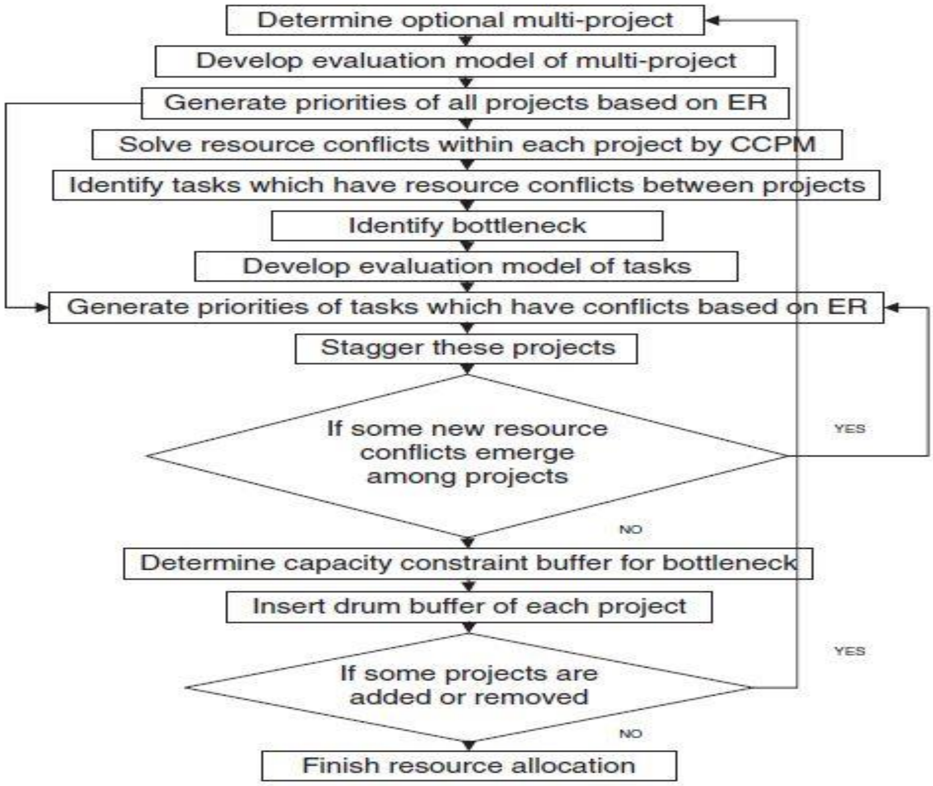

Figure 3-1.Decision model of multi-project resources-based constrained scheduling.

The most important tasks of CCPM in engineering projects are to protect the activity from being late, to prevent employees from being late in tasks under the pretext of being busy and to prevent late finishing activities due to multitasking (Ahlemann, 2013). In order to reduce the duration of the project, taking into account the constraints in resources and other constraints, Roghanian, Alipour and Rezaei (2017) proposed a model of the resource-constrained project scheduling problem (RCPSP). The output of this model determines the time required for the project, and then a new model is made for the buffer by the square root of the sum of squares (SSQ) method. Figure 3-2 explain the comparison between PERT/CPM and TOC. Fragility theory is proposed in the critical chain in order to solve the project delay problems that occur due to the non-zero buffer zone. This theory consists of three methods. In the beginning, it is proposed that the construction process is fragile and the fragility of the construction process is analyzed, then an integrated impact rate is presented to describe the uncertainty in construction. Finally, modified models are selected for the project's temporary buffer and feed buffer. The results showed that this process would reduce the construction period (Peng & long, 2022). A new framework was created for the buffer management based on the index of table stability and resource costs. In this context, a decision is taken to allocate resources to reduce the cost of resources. Delaying the activity leads to taking corrective measures. A rescheduling procedure is implemented based on interactive resources to restore the work and performance of the project (Hu, 2017). A study by Taghipour, Amin, Seraj and delivand (2020) Says that Critical Chain Project Management (CCPM) follows the rule that project completion timelines are greatly impacted by uncertainty in activity durations when it comes to modifying planning methodologies with the overall goal of reducing project deadline delays. CCPM acknowledges the potential obstacles that may arise from inaccurate demands, guidelines, and activity estimates. It also emphasizes the critical role that experience, knowledge, and collaboration play in successful project management.

Peng and Huang (2014) addresses the recurring challenge of suboptimal schedules and unmet completion deadlines within the framework of Critical Chain Project Management (CCPM). The primary focus is on presenting an optimal methodology for generating the critical chain schedule. Specifically, the float time associated with the non-critical chain serves as the key consideration for establishing feeding buffers, resulting in a notably streamlined process for developing the critical chain project plan. A study was conducted by Su, Lucko and Thompson (2016) that included the prevalent issue of delay in the construction industry, with a particular focus on the application and effectiveness of Critical Chain Project Management (CCPM) in mitigating delays. While CCPM has long been proposed as a theoretical solution, its actual preventive capabilities lack comprehensive scientific analysis. This paper outlines a formal, systematic process consisting of four modules for evaluating CCPM performance. Using Monte Carlo simulations on timescales of varying complexity, delays are examined with respect to calculated temporal bounds. Contrary to expectations, the results indicate that CCPM rarely delivers on its promises, with exceedances observed in both critical and non-critical chains.

Same study by Taghipour, Amin, Seraj and Delivand (2020), Critical Chain Project Management (CCPM), which acknowledges time uncertainty, is a viable solution to project delays. Cultural changes are considered critical to the success of CCPM, and the suggested algorithm provides reasonable time and buffer estimates. Assuring stakeholder satisfaction and cutting project duration without changing constraints, CCPM is regarded as a cost-effective method. Taking costs, earnings, and break-even point into account is emphasized as the first stage in implementing CCPM. Studies on the application of Critical Chain to project management have been conducted; these studies have identified areas for improvement and the current state of development. He views as arbitrary Goldratt's oversimplified suggestion to establish the project buffer at half the project period. The average activity time for crucial chain operations and the project buffer estimate have a direct correlation, as confirmed by the analysis. Although Critical Chain has been successful in cutting project length, Goldratt's approach has to be improved. According to the idea, sizing should be done differently, accounting for project kinds and uncertainties as well as management's attitude toward risk. (Yao & Shou, 2000)

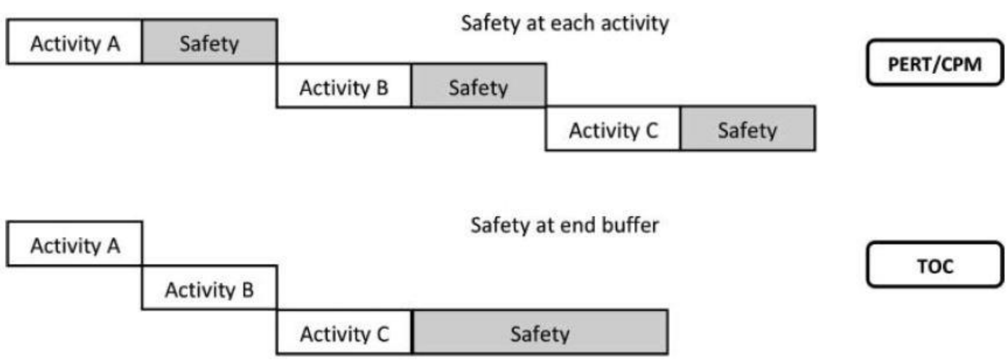

Figure 3-2. PERT/CPM and TOC comparison.

CCPM was used in risk assessment and theory of constraints in the transformation process of the IGCC (Integrated Gasification Combined Cycle factory. The aim of this use was to determine the method of work priorities to reduce the risks related to accidents in factories. CCPM allowed the company, through its method, to increase the quality of work, improve its safety, and reduce the time and cost required (Bevilacqua, Ciarapica, & Giacchetta, 2009).

Another paper presents the results of an analysis between the critical chain management and the traditional scheduling of the critical path for the construction of several marinas in Poland. The study showed that project planning based on CCPM will allow flexible scheduling of individual projects and control of temporary buffers, which leads to improved management by supervision and reducing many negative tasks that affect the buffers (Araszkiewicz, 2017).

Procurement work has been proposed in the engineering projects and building construction (EPC) by combining the concept of supply chain management with the critical chain. This proposal is represented in three different approaches, which are scientific, cultural and technological, with attention to buffers management to improve the management of uncertainty in purchases (Yeo & Ning, 2002). Figure 3-3 shows the process model of EPC.

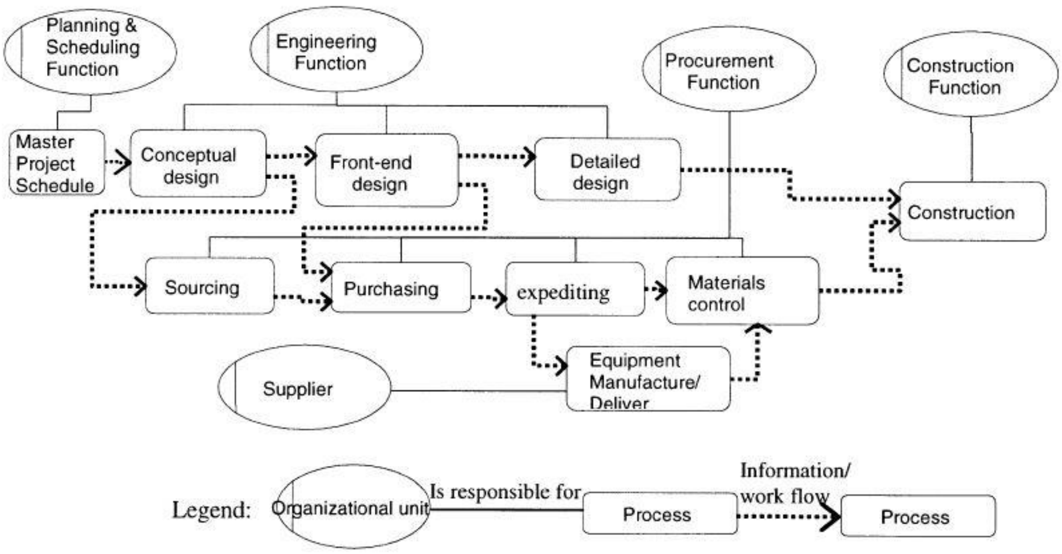

Figure 3-3. An EPC process model.

CCPM was used to manage tools and techniques in infrastructure projects in Greece, especially in institutions that do not apply practices and methods of project management. 27 infrastructure projects and highway projects about 300 km were analyzed, as well as in tunnels and bridges in cities. CCPM contributed to Reducing project time, which leads to lower indirect costs, and lower direct costs due to better employment of resources. (Petroutsatou, 2022).

A CCPM unit enhances a traditional project management course by highlighting the potential drawbacks of conventional scheduling techniques. From a pedagogical perspective, contrasting and comparing CCPM with effective practices, it motivates students to learn and think deeply (Millhiser & Szmerekovsky,, 2012).

Study by Salama, Salah, and Moselhi (2018) presents a new technique that combines the scheduling approaches of Critical Chain Project Management (CCPM) with the Last Planner System (LPSM). The approach accomplishes a number of goals, such as minimizing project duration by utilizing the aggressiveness of CCPM, adhering to the continuity constraint specified by LPSM, identifying multiple critical sequences affected by resource constraints, and allocating project and feeding buffers strategically. Paper by Salama, Salah, and Moselhi (2021) introduces an innovative method for tracking and controlling modular construction projects, integrating building information modeling with Last Planner System (LPS), Linear Scheduling Method (LSM), and Critical Chain Project Management (CCPM). The approach considers resource continuity constraints and activity duration uncertainties. Demonstrated through a case example, it outperforms Monte Carlo simulation in baseline duration prediction, revealing a 5% project delay and 2.5% cost overrun. Unique integration and reliability metrics (critical percent plan complete and buffer index) “PPCcr and BI” enhance forecasting accuracy, providing a systematic procedure for look-ahead schedules and robust tracking, including quantitative cost analysis for comprehensive project monitoring.

Ghoddousi, Ansari and Makui (2017) Introduces an inventive buffer sizing method grounded in flexibility, complexity, robustness, and dependency metrics, offering a systematic approach to determine project and feeding buffer sizes in risk-prone conditions. Employing network-based risk interaction analysis, the proposed method quantifies impacts on time buffer sizes. Simulation experiments validate the efficiency of the model, and comparative results demonstrate the efficacy of the robust multi-attribute buffer sizing approach in a real-world project. The discussion delves into the strengths and limitations of the proposed buffer sizing method, affirming its ability to yield more rational and cost-effective time buffer sizes. This underscores its capacity to effectively manage project planning amid uncertainties. For Critical Chain Project Management (CCPM), a novel buffer sizing process is proposed by She, Chen and Hall (2021). This process is essential for precise project timelines and competitive bids. It avoids excessive buffers and inconsistent execution, in contrast to earlier techniques. It calculates feeding buffer sizes from noncritical chains using network decomposition and adds safety margins for the project buffer. Greater accuracy in project duration estimation is demonstrated by computational testing, which leads to smaller feeding buffers and an uncontested critical chain. Delays in spending and decreases in work-in-process, rework, and multitasking are further advantages.

Tukel, Rom and Eksioglu (2006) investigates several buffer size strategies, contrasting traditional methods with novel ideas. It evaluates how they will affect estimated completion timelines and the possibility of fulfilling deadlines. The paper discovers that taking project features into account when sizing buffers enhances scheduling without adding more complexity through simulation on the Patterson dataset. On the other hand, due to greater buffer sizes, straightforward techniques like C&PM could result in longer completion times. Future enhancements, such incorporating economic concerns and investigating rescheduling throughout project execution, are suggested by the research. All things considered, this study adds to the literature on resource-constrained project scheduling by presenting essential chain concepts for more research.

Study by Luiz, de Souza, Jugend and Salgado (2019) conducts a comprehensive analysis of the Critical Chain Project Management (CCPM) literature, utilizing bibliometric tools from Scopus and Web of Science databases. Through co-citation and keyword co-occurrence maps, five clusters emerge: Fundamentals of Critical Chain, Scheduling, Operations Research, Multi-project and Network, and General Project Management. The prevalent keywords include "project management," "critical chain," "scheduling," and "theory of constraints." A proposed evolutive framework categorizes CCPM literature into three stages: Conceptual, Deepening of Applications, and Methodological Maturity. This systematic approach provides a rigorous organization of CCPM literature, offering insights into the evolving themes and directing future research toward current gaps and areas of interest. Another study by Luiz, de Souza, Jugend and Salgado (2019) explores the impact of Critical Chain Project Management (CCPM) practices on new product development performance in Brazilian companies. Surveying 79 innovative firms, it reveals significant, positive correlations between CCPM adoption and performance factors. Notably, CCPM shows a stronger link with product portfolio management (PPM) performance than traditional methods. The findings suggest CCPM practices indirectly contribute to enhanced product development programs through improved PPM. The study contributes empirical evidence that specific CCPM practices correlate with superior organizational performance, emphasizing the practical value for managers in prioritizing CCPM practices for enhanced PPM performance.

Another study by Ghaffari and Emsley (2015) critically reviews 140 CCPM papers using hierarchical coding, revealing ongoing but slower-paced research. Six approach categories are identified, emphasizing improving studies. Shortcomings addressed form a list of 21 areas for future CCPM development. The study traces CCPM's journey, noting an evolution from introductory to improvement-focused research. Authors consistently report on CCPM implementation, deployment, and empirical verification. The paper advocates future research on method enhancement and detailed case reporting to address CCPM's identified shortcomings comprehensively.

In order to reduce uncertainty in project management, Iranmanesh, Mansourian and Kouchaki (2016) examines Critical Chain approaches. It focuses in particular on the location and size of buffers strategically. Although buffers are typically inserted at the end of the critical chain and feed chains, it is important to determine the ideal size for them since the critical chain concept may not work as intended if the size is not adequate. While large buffer widths might defend against uncertainty, they can also result in longer lead times and wasteful resource use. On the other hand, using modest buffer widths could not provide projects with enough uncertainty protection. The effectiveness of this method is compared with conventional approaches such as C&P, RSEM, APRT, and APD. Simulation results demonstrate the proposed method's suitability for buffer sizing, indicating its potential as an effective strategy for managing project uncertainties. Adaptive processes are described in the following two approaches: resource tightness and network density with sophisticated basis. Tukel (2006) simply utilized a new coefficient K that was multiplied by the computed standard deviation to obtain the buffer size, and they agreed on the root square technique approach. Network complexity is represented by calculating factor K, which is the ratio of the total number of precedence relationships to the total number of tasks. Resource tightness is represented by calculating k, which is the ratio of the total resource utilization to the total resource availability for each resource. Comparative analysis reveals that in high-uncertainty project environments, the likelihood of fulfilling scheduled completion deadlines for big projects might be as low as 60–70%. (Korany, Mossa, Etman, & Taher, 2016).

Table 3-1 represent the summarizing of the strategy used by resources and findings.

Table 3-1. Strategies and findings

Author	Strategy	Findings
(Bevilacqua, Ciarapica, & Giacchetta, 2009)	risk assessment and theory of constraints in the transformation process of the IGCC.	increase the quality of work, improve its safety, and reduce the time and cost required.
(Araszkiewicz, 2017)	Using the CCPM method for the construction of several marinas.	improved management by supervision and reducing many negative tasks that affect the buffers.
(Yeo & Ning, 2002)	Procurement in the engineering projects and building construction (EPC).	improve the management of uncertainty in purchases.
(Petroutsatou, 2022)	manage tools and techniques in infrastructure projects in Greece.	lower indirect costs, and lower direct costs due to better employment of resources.
(Sarkar, Shraddha , & Jha, 2021)	Using CCPM with the theory of constraints (TOC). “Critical Chain Technology”.	generate buffers with suitable sizes and enough robustness to conduct the currently used buffer sizing procedures.
(Dalouchei, Mousavi, Antucheviciene, & Minaei, 2022)	scheduling construction projects by combining resource limitations and the critical chain management technique.	increase quality and reduce project time.
(Shanlin & Fu, 2014)	CCPM with logic of evidence(LOE) in automotive industry.	inding solutions to the problem of material conflict with the existence of multiple projects
(Roghanian, Alipour , & Rezaei, 2017)	model of the resource-constrained project scheduling problem (RCPSP) with (SSQ).	reduce the duration of the project.
(Peng & long, 2022)	Fragility theory in the critical chain.	reduce the construction period.

(Ansari, Khalilzadeh , & Hosseini , 2022)	CCPM and buffer sizing in the construction of railways in the metro with “RESM”	reduced the project time by 3%
(Hu, 2017)	Framework for the buffer management based on the index of table stability and resource costs.	Delaying the activity leads to taking corrective measures.
(Ordon˜ez, 2019)	(CCPM) to minimize the inefficiencies identified in traditionalproject management	better time estimation of activities and facilitates the allocation of critical resources
(Abidah & Al Hazza, 2021)	analyzing the schedule provided and then implementing CCS and BM using four different methods	assist the project manager in determining the project completion rate and timeline buffer penetration.

Based on the research, it can be argued studies on finding the appropriate buffer size for CCPM are still scarce. With this motivation the methodology of this thesis is designed in order to discuss the efficiency of various proposed buffer sizing techniques.

4. METHODOLOGY

The following flowchart explains the steps that will be implemented to clarify the objectives of this thesis. It begins by explaining the two methods for scheduling, then implementing each of them on the same project, and finally arriving at the results and comparing them.

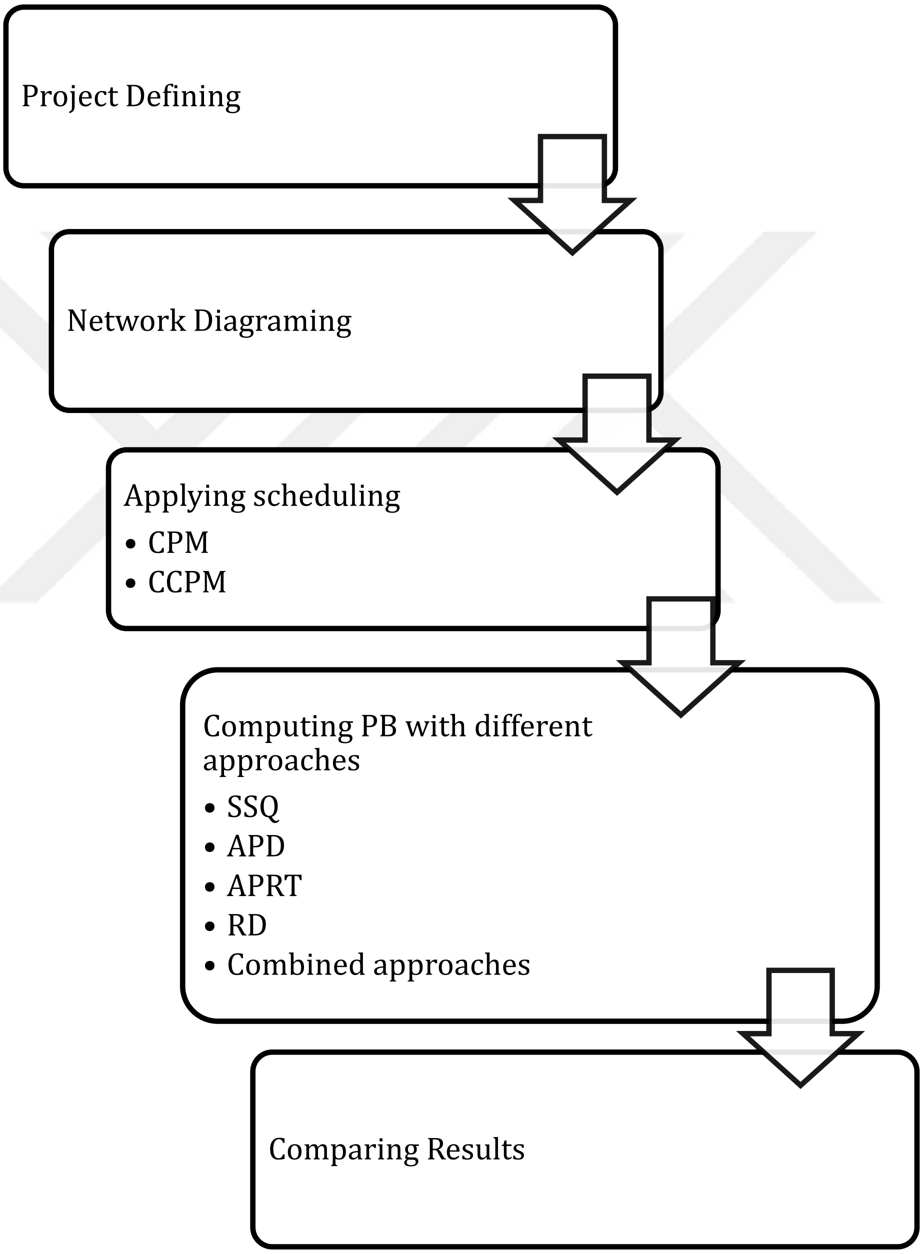

Figure 4-1. Flowchart of the methodology

4.1. Project Defining

One of the most important basics in applying project management methodology is a clear understanding of the project under study. A complete overview of the project chosen for this study is presented, through which the project objectives, owners, project scope, project timeline for each activity, and project budget are determined, based on understanding and defining the project. Activities are determined by identifying the activity that must be completed before starting the current activity.

4.1.1. Sequencing activities for "Network diagram"

In this section, a network diagram is developed to visualize the sequence of activities required for the project. The network diagram illustrates the preceding relationships between different tasks and activities, highlighting their dependencies and the flow of work throughout the project lifecycle. By sequencing activities effectively, the aim is to identify the critical path, which represents the longest path through the project network and determines the minimum duration required to complete the project. MS Project software is used to link the activities together with Finish to Start relationship, and clarify the beginning and end of each activity.

There can be more than one way to link activities to each other, and these are:

- Finish-to-Start (FS): This is the most common relationship where one activity must finish before another can start.
- Start-to-Start (SS): In this relationship, two activities can start simultaneously.
- Finish-to-Finish (FF): Two activities must finish simultaneously.
- Start-to-Finish (SF): This relationship is less common, where one activity must start for another to finish.

4.1.2. Computing activity durations

After defining the predecessor relations, the durations of individual activities within the construction project are estimated. Accurate estimation of activity durations is critical to developing a realistic project schedule and managing project schedules effectively. Various techniques, such as historical data analysis, expert judgment, and parametric estimation can be used to estimate the time needed for each activity. In addition, factors such as resource availability, task complexity and potential risks are taken into account to ensure comprehensive and reliable estimates. In engineering projects, the time required to complete the activity is calculated initially through the number of workers and the productivity of each worker. PERT theory is used to determine the time required for each activity, which consists of three time estimates such as, optimistic, pessimistic, and most likely, and the equation for computing the task duration is as follows:

$$t_e = \frac{t_o + 4t_m + t_p}{6}$$

Where:

t_e = the expected time

t_o = Optimistic time

t_m = Most likely time

t_p = Pessimistic time

4.2. Project Scheduling

4.2.1 Scheduling with CPM Method

The Critical Path Method (CPM) is an essential tool in project management, providing a structured approach to scheduling complex projects. By defining the critical path, CPM provides insights into project duration and scheduling constraints.

The critical path is defined as the longest path in the activity network diagram and the shortest time to complete the project. It is calculated by computing the earliest start and finish times and the latest start and finish times for each activity in the project. First, the critical activities are determined by calculating the slack duration for each activity and then Critical Path(s) of the project is determined which consists of the path with activities that have zero (0) slack. The duration of slack time for each task is calculated with the following simple formula;

Slack time = Late finish – Early finish.

The MS Project software is used to determine the critical path by defining all activities and their duration on the project. After completing the critical path determination, the project duration is calculated in days and hours. The start and end dates of the project, the duration of the project, and the activities used are indicated.

4.2.1. Scheduling with CCPM Method

After CPM approach, the project duration is calculated by Critical Chain Project Management (CCPM) method by adopting resource leveling. CCPM provides innovative solutions to manage project constraints and optimize resource utilization. To improve project performance. It focuses on determining the key sequence of activities and effectively allocating resources. This part delves into the concepts and implementations of CCPM within the framework of the case project, emphasizing its efficacy in enhancing project results.

The project planning begins and the connection of activities to each other is determined. The project plan is drawn using the MS Project software. This plan is similar to the CPM method. The project is planned by defining the project objectives, scope, and resource constraints. This stage aims to allocate resources and manage risks throughout the life of the project.

Resource management is considered one of the most important pillars in critical chain management. A resource leveled network is created for the project to determine the resources needed for it, then the activities associated with the same resources are identified. A plan for the project network is drawn based on similar resource activities, which works to avoid multiple tasks or conflicts of activities.

After completing the resource network drawing, the most likely times (t_m) are used for computing the project completion time since CCPM approach differs from previous theories in terms of time; optimistic or pessimistic estimates are not used. The CCPM relies on determining a realistic duration for each activity in the project based on the resources available to it and performance data. Previously, this works to develop more tight project schedules and adding buffer to that tight completion time enhance project results and mitigate schedule risks. Same approach that considers the slack times are implemented to find the critical path which is named ‘Critical Chain’. AT this step the completion time of the project is donated withCT_0.

4.3. Computing Project Buffer (PB)

Project Buffer (PB) which is added after the tight critical chain is computed using four different approaches described in the following sections. It is noted that the Project Buffer's size must not be less than 25% of the critical chain's total size. Therefore, the PB size is increased to this minimal amount if the result of the calculation leads to a number that is less than 25% of the chain.

4.3.1. Square Root of Sum of the Squares (SSQ)

Square Root of Sum of the Squares (SSQ) method is the widely used approach for calculating the buffer size. The buffer is calculated by the following equation:

$$PB_{SSQ} = \sqrt{\sum D_i^2}$$

$$D_i = t_{pi} - t_{mi}$$

Where:

PB_{SSQ} = Project Buffer size (duration) via SSQ method

D_i = the amount of shortened duration of an activity i on the critical chain

t_{pi} = Pessimistic time of activity i on the critical chain

t_{mi} = Most likely time of activity i on the critical chain

The completion time (CT_{SSQ}) will be;

$$CT_{SSQ} = CT_0 + PB_{SSQ}$$

4.3.2. Adaptive Procedure with Density (APD)

This method takes into account project characteristics and uncertainty, which reflects resource constraints and network size, in determining buffer sizes. The approach involves calculating the Resource Utilization Factor (RF) and considering the ratio of precedence relationships to tasks to effectively address these issues. The number of relationships associated with critical activities in the project is calculated and the theory is applied to find the new buffer for the project (Tukel, Rom, & Eksioglu, 2006).

APD method is based on network complexity called the “density”, that considers the number of predecessors present in critical activities. The buffer is calculated by the following equation:

PB_{APD}= K x PB_{SSQ}

NC = TOTPRE/NUMTASK

K = 1 + NC

Where:

PB_{SSQ}= Project Buffer size (duration) via SSQ method

PB_{APD}= Project Buffer size (duration) via APD method

NC = Network complexity

*TOTPR*E = the total number of precedence relationships defined on the sub-network feeding into the critical chain.

NUMTASK = the total number of tasks on the sub-network.

K= calculated factor

The completion time (CT_{APD}) will be;

CT_{APD} = CT_0+PB_{APD}

4.3.3. Adaptive Procedure with Resource Tightness (APRT)

Resource tightness is reflected by calculating k value as the ratio of total resource usage to the total resource availability for each resource (Tukel, Rom, & Eksioglu, 2006). The buffer is calculated by the following equation:

PB_{APRT}= K x PB_{SSQ}

RF (q) = $\frac{\sum_{i=1}^{\#critical\ activities}(Total\ number\ of\ workers\ on\ activity\ i * t_i)}{\mathrm{CT}_0 * Total\ number\ of\ workers\ on\ the\ project}$

Max RF (q⬚) = ŕ

K = 1 + ŕ

Where:

RF = Resource utilization factor.

t_i= Duration for activity i.

K= calculated factor

ŕ = resource usage

The completion time (CT_{APRT}) will be;

$$CT_{APRT} = CT_0 + PB_{APRT}$$

4.3.4. Relative Dispersion (RD)

Relative dispersion is considered one of the best appropriate indicators of uncertainty regarding the duration of an activity. Activities with high uncertainty have high relative dispersion, while activities with low uncertainty have low relative dispersion. Therefore, relative dispersion is used to classify activities according to the table 4.1 shown below (Yao & Shou, 2000).

Table 4.1. Classification of uncertainty

Class	Level of uncertainty	Lower bound (related to x_a)	Upper bound (related to x_b)
A	Very Low	-5%	+20%
B	Low	-10%	+30%
C	High	-15%	+40%
D	Very High	-20%	+50%

$$\sigma_i{}^2 = \left(\frac{t_P - t_O}{6}\right)^2$$

$$\sigma_p = \sqrt[2]{\sum \sigma_{i\ critical}{}^2}$$

$$RD = \frac{\sigma_p}{CT_0}$$

Where

RD = Relative dispersion

σ_p = Standard deviation of the project

σ_i^2= Variance of activity *i*.

t_o = Optimistic time

t_p = Pessimistic time

Afterwards, buffer size is increased based on the uncertainty class of the project and the preferred safety level given in the table below.

Table 4-2.Buffer size increase (K factor) for different uncertainty classes

	Low safety	**Median safety**	**High safety**
A	4%	8%	12%
B	12%	24%	36%
C	20%	40%	60%
D	28%	57%	85%

PB_{RD} = K x PB_{SSQ}

Where:

K is a safety factor added to PB_{SSQ} as Goldratt's method.

The completion time (CT_{RD}) will be;

CT_{RD} = CT_0+PB_{RD}

4.4. Comparative Results

In the final stage comparison tables are developed for alternative buffers calculated by four different approaches. Also, the results obtained from the CPM method are compared with and without resources levelling and the results obtained from the CCPM methods in terms of the duration of the project, the effectiveness of each, and its benefits and disadvantages.

5. IMPLEMENTATION AND RESULTS

In this section, a detailed examination of a real construction project is presented to explore the practical application of both the CPM and CCPM applying four buffer sizing alternatives. This study provides real insight into how these different approaches are used and shows the strengths and weaknesses of each and how they affect project completion.

5.1. The Case Project

The process of project management in Palestine is considered one of the most seen difficulties faced by engineering project owners, due to the political, economic, and logistical challenges they face. These challenges include limited access to resources, political instability, and bureaucratic obstacles, which greatly affects project timetables and budgets. In light of this, applying the principles of critical chain project management (CCPM) to a mall project in Palestine will provide a convincing case study in contrast to the traditional methods used in project management. In this case, the focus is on resources, working to avoid or mitigate risks, and improving the project schedule, among the most important. The risks faced in construction projects include the lack of materials throughout the life of the project. From here comes the role of CCPM, which works to identify and manage project constraints in order to be consistent with the challenges facing the region. The focus of this case study is on the benefits of adopting CCPM for project management in Palestine.

The mall studied as the case project consists of 14 floors, three underground floors consisting of a parking lot, a settlement floor, a ground floor, and a mezzanine floor, and 9 floors above the ground. Construction of the project began in 2018 and was delivered in 2021. It is expected to be completed with a budget of 2.5 million $ and 540 work days which is less than 2 years considering the holidays.

The project consists of 428 activities (provided in Appendix); for the simplification objective, these activities are merged into packages. All activities related to structure works include the construction of columns, walls, and slab work for each floor. Each activity is divided into shuttering, reinforcement, pouring, and de-shuttering. The activities collected in one activity to facilitate the process of applying the principles of the critical chain are provided in the following tables; from Table 5-1 to Table 5-10.

Table 5-1. Base construction activities

Base Construction							
Outline number	Activity Name	t_p	t_m	t_o	t_e	t	Predecessor
3.1	Foundation						
3.1.1	Shuttering	4	3	1	2.83	3	
3.1.2	Steel fixing	5	3	2	3.17	3	3.1.1
3.1.3	Concrete pouring	1	1	1	1.00	1	3.1.2
3.1.4	De-shuttering	4	3	2	3.00	3	3.1.3
3.2	Column necks						
3.2.1	Shuttering	4	3	2	3.00	3	3.1.4
3.2.2	Steel fixing	5	3	2	3.17	4	3.2.1
3.2.3	Concrete pouring	1	1	1	1.00	1	3.2.2
3.2.4	De-shuttering	3	1	1	1.33	2	3.2.3
3.3	Slob On Grade						
3.3.1	Shuttering	1	1	1	1.00	1	3.5.4
3.3.2	Steel fixing	3	2	2	2.17	3	3.3.1
3.3.3	Concrete pouring	1	1	1	1.00	1	3.3.2
3.3.4	De-shuttering	1	1	1	1.00	1	3.3.3
3.4	Ground beams						
3.4.1	Shuttering	5	4	2	3.83	4	3.2.4
3.4.2	Steel fixing	3	2	2	2.17	3	3.4.1
3.4.3	Concrete pouring	1	1	1	1.00	1	3.4.2
3.4.4	De-shuttering	3	2	1	2.00	2	3.4.3
3.5	Shear wall (TOF)						
3.5.1	Shuttering	4	3	2	3.00	3	3.4.4
3.5.2	Steel fixing	3	2	1	2.00	2	3.5.1
3.5.3	Concrete pouring	1	1	1	1.00	1	3.5.2
3.5.4	De-shuttering	3	2	1	2.00	2	3.5.3
Total duration		56	40	28	40.66	41	

Table 5-2. Parking floor 3 activities

Parking floor 3							
Outline number	Activity Name	t_p	t_m	t_o	t_e	t	Predecessor
4.1	Columns						
4.1.1	Shuttering	3	2	1	2.00	2	3.3.4
4.1.2	Steel fixing	3	1	1	1.33	2	4.1.1
4.1.3	Concrete pouring	1	1	1	1.00	1	4.1.2
4.1.4	De-shuttering	2	1	1	1.17	2	4.1.3
4.2	Beams						
4.2.1	Shuttering	3	2	2	2.17	3	4.1.4
4.2.2	Steel fixing	5	4	2	3.83	4	4.2.1
4.2.3	Concrete pouring	1	1	1	1.00	1	4.3.2
4.2.4	De-shuttering	1	1	1	1.00	1	4.3.3
4.3	Slab						
4.3.1	Shuttering	6	5	3	4.83	5	4.1.4
4.3.2	Steel fixing	8	6	3	5.83	6	4.3.1
4.3.3	Concrete pouring	1	1	1	1.00	1	4.3.2
4.3.4	De-shuttering	3	2	1	2.00	2	4.3.3
4.4	Stair						
4.4.1	Shuttering	1	1	1	1.00	1	4.3.1
4.4.2	Steel fixing	2	1	1	1.17	2	4.4.1
4.4.3	Concrete pouring	1	1	1	1.00	1	4.3.2
4.4.4	De-shuttering	1	1	1	1.00	1	4.4.3
Total Duration		42	31	22	31.33	32	

Note: For each Parking floor in the project need 32 days to complete structure works, the Sum of duration need to finish structure work for all parking is equal 96 days.

Table 5-3. Basement floor activities.

Basement floor activities							
Outline number	Activity Name	t_p	t_m	t_o	t_e	t	Predecessor
5.1	Columns						
5.1.1	Shuttering	4	2	1	2.17	3	4.3.3
5.1.2	Steel fixing	3	2	2	2.17	3	5.1.1
5.1.3	Concrete pouring	1	1	1	1.00	1	5.1.2
5.1.4	De-shuttering	1	1	1	1.00	1	5.1.3
5.2	Beams						
5.2.1	Shuttering	2	1	1	1.17	2	5.1.4
5.2.2	Steel fixing	4	3	2	3.00	3	5.2.1
5.2.3	Concrete pouring	1	1	1	1.00	1	5.3.2
5.2.4	De-shuttering	1	1	1	1.00	1	5.2.3
5.3	Slab						
5.3.1	Shuttering	4	3	1	2.83	3	5.1.4
5.3.2	Steel fixing	4	2	2	2.33	3	5.3.1
5.3.3	Concrete pouring	1	1	1	1.00	1	5.3.2
5.3.4	De-shuttering	2	2	1	1.83	2	5.3.3
5.4	Stair						
5.4.1	Shuttering	1	1	1	1.00	1	5.3.1
5.4.2	Steel fixing	1	1	1	1.00	1	5.4.1
5.4.3	Concrete pouring	1	1	1	1.00	1	5.3.2
5.4.4	De-shuttering	1	1	1	1.00	1	5.4.3
Total Duration		32	24	19	24.50	25	

Table 5-4. Ground floor activities.

Ground floor activities							
Outline number	Activity Name	t_p	t_m	t_o	t_e	t	Predecessor
6.1	Columns						
6.1.1	Shuttering	3	2	1	2.00	2	5.3.3
6.1.2	Steel fixing	3	2	2	2.17	3	6.1.1
6.1.3	Concrete pouring	1	1	1	1.00	1	6.1.2
6.1.4	De-shuttering	2	1	1	1.17	2	6.1.3
6.2	Beams						
6.2.1	Shuttering	2	1	1	1.17	2	6.1.4
6.2.2	Steel fixing	4	2	1	2.17	3	6.2.1
6.2.3	Concrete pouring	1	1	1	1.00	1	6.3.2
6.2.4	De-shuttering	1	1	1	1.00	1	6.2.3
6.3	Slab						
6.3.1	Shuttering	3	2	2	2.17	3	6.1.4
6.3.2	Steel fixing	4	3	1	2.83	3	6.3.1
6.3.3	Concrete pouring	1	1	1	1.00	1	6.3.2
6.3.4	De-shuttering	2	2	1	1.83	2	6.3.3
6.4	Stair						
6.4.1	Shuttering	1	1	1	1.00	1	6.3.1
6.4.2	Steel fixing	1	1	1	1.00	1	6.4.1
6.4.3	Concrete pouring	1	1	1	1.00	1	6.3.2
6.4.4	De-shuttering	1	1	1	1.00	1	6.4.3
Total Duration		31	23	18	23.50	24	

Table 5-5. Mezzanine floor activities.

Mezzanine floor activities							
Outline number	Activity Name	t_p	t_m	t_o	t_e	t	predecessor
7.1	Columns						
7.1.1	Shuttering	2	1	1	1.17	2	6.3.3
7.1.2	Steel fixing	3	2	1	2.00	3	7.1.1
7.1.3	Concrete pouring	1	1	1	1.00	1	7.1.2
7.1.4	De-shuttering	1	1	1	1.00	2	7.1.3
7.2	Beams						
7.2.1	Shuttering	3	1	1	1.33	2	7.1.4
7.2.2	Steel fixing	2	1	1	1.17	3	7.2.1
7.2.3	Concrete pouring	1	1	1	1.00	1	7.3.2
7.2.4	De-shuttering	1	1	1	1.00	1	7.2.3
7.3	Slab						
7.3.1	Shuttering	3	2	2	2.17	3	7.1.4
7.3.2	Steel fixing	1	1	1	1.00	3	7.3.1
7.3.3	Concrete pouring	1	1	1	1.00	1	7.3.2
7.3.4	De-shuttering	2	2	1	1.83	2	7.3.3
7.4	Stair						
7.4.1	Shuttering	1	1	1	1.00	1	7.3.1
7.4.2	Steel fixing	1	1	1	1.00	1	7.4.1
7.4.3	Concrete pouring	1	1	1	1.00	1	7.3.2
7.4.4	De-shuttering	1	1	1	1.00	1	7.4.3
Total Duration		25	19	17	19.67	20	

Table 5-6. Typical floor activities.

Typical floor							
Outline number	Activity Name	t_p	t_m	t_o	t_e	t	Predecessor
8.1	Columns						
8.1.1	Shuttering	2	1	1	1.17	2	7.3.3
8.1.2	Steel fixing	3	2	2	2.17	3	8.1.1
8.1.3	Concrete pouring	1	1	1	1.00	1	8.1.2
8.1.4	De-shuttering	1	1	1	1.00	1	8.1.3
8.2	Beams						
8.2.1	Shuttering	3	2	1	2.00	2	8.1.4
8.2.2	Steel fixing	2	1	1	1.17	2	8.2.1
8.2.3	Concrete pouring	1	1	1	1.00	1	8.3.2
8.2.4	De-shuttering	3	1	1	1.33	2	8.2.3
8.3	Slab						
8.3.1	Shuttering	3	2	1	2.00	2	8.1.4
8.3.2	Steel fixing	5	3	2	3.17	4	8.3.1
8.3.3	Concrete pouring	1	1	1	1.00	1	8.3.2
8.3.4	De-shuttering	3	1	1	1.33	2	8.3.3
8.4	Stair						
8.4.1	Shuttering	2	1	1	1.17	2	8.3.1
8.4.2	Steel fixing	1	1	1	1.00	1	8.4.1
8.4.3	Concrete pouring	1	1	1	1.00	1	8.3.2
8.4.4	De-shuttering	2	1	1	1.17	2	8.4.3
Total Duration		34	21	18	22.66	23	

Note: For each typical floor in the project need 23 day to complete structure works, the sum of duration need to finish structure work for 5 typical floor is equal to 115 days.

Table 5-7. Sixth floor activities.

Six floor activities							
Outline number	Activity Name	t_p	t_m	t_o	t_e	t	Predecessor
9.1	Columns						
9.1.1	Shuttering	3	2	1	2.00	2	8.3.3
9.1.2	Steel fixing	2	1	1	1.17	3	9.1.1
9.1.3	Concrete pouring	1	1	1	1.00	1	9.1.2
9.1.4	De-shuttering	1	1	1	1.00	2	9.1.3
9.2	Beams						
9.2.1	Shuttering	3	1	1	1.33	2	9.1.4
9.2.2	Steel fixing	3	2	1	2.00	3	9.2.1
9.2.3	Concrete pouring	1	1	1	1.00	1	9.3.2
9.2.4	De-shuttering	1	1	1	1.00	1	9.2.3
9.3	Slab						
9.3.1	Shuttering	2	2	1	1.83	3	9.1.4
9.3.2	Steel fixing	2	1	1	1.17	3	9.3.1
9.3.3	Concrete pouring	1	1	1	1.00	1	9.3.2
9.3.4	De-shuttering	2	1	1	1.17	2	9.3.3
9.4	Stair						
9.4.1	Shuttering	1	1	1	1.00	1	9.3.1
9.4.2	Steel fixing	1	1	1	1.00	1	9.4.1
9.4.3	Concrete pouring	1	1	1	1.00	1	9.3.2
9.4.4	De-shuttering	1	1	1	1.00	1	9.4.3
Total Duration		26	19	16	19.67	20	

Table 5-8. Seventh floor activities.

Seven floor activities							
Outline number	Activity Name	t_p	t_m	t_o	t_e	t	Predecessor
10.1	Columns						
10.1.1	Shuttering	3	1	1	1.33	2	9.3.3
10.1.2	Steel fixing	2	1	1	1.17	3	10.1.1
10.1.3	Concrete pouring	1	1	1	1.00	1	10.1.2
10.1.4	De-shuttering	1	1	1	1.00	2	10.1.3
10.2	Beams						
10.2.1	Shuttering	2	2	1	1.83	2	10.1.4
10.2.2	Steel fixing	3	2	1	2.00	3	10.2.1
10.2.3	Concrete pouring	1	1	1	1.00	1	10.3.2
10.2.4	De-shuttering	1	1	1	1.00	1	10.2.3
10.3	Slab						
10.3.1	Shuttering	2	2	1	1.83	3	10.1.4
10.3.2	Steel fixing	2	1	1	1.17	3	10.3.1
10.3.3	Concrete pouring	1	1	1	1.00	1	10.3.2
10.3.4	De-shuttering	2	1	1	1.17	2	10.3.3
10.4	Stair						
10.4.1	Shuttering	1	1	2	1.17	1	10.3.1
10.4.2	Steel fixing	1	1	1	1.00	1	10.4.1
10.4.3	Concrete pouring	1	1	1	1.00	1	10.3.2
10.4.4	De-shuttering	1	1	1	1.00	1	10.4.3
Total Duration		25	19	17	19.67	20	

Table 5-9. Roof floor activities.

Roof floor activities							
Outline number	Activity Name	t_p	t_m	t_o	t_e	t	Predecessor
11.1	Columns						
11.1.1	Shuttering	2	1	1	1.17	2	10.3.3
11.1.2	Steel fixing	2	1	1	1.17	3	11.1.1
11.1.3	Concrete pouring	1	1	1	1.00	1	11.1.2
11.1.4	De-shuttering	1	1	1	1.00	2	11.1.3
11.2	Beams						
11.2.1	Shuttering	2	1	1	1.17	2	11.1.4
11.2.2	Steel fixing	2	2	1	1.83	3	11.2.1
11.2.3	Concrete pouring	1	1	1	1.00	1	11.3.2
11.2.4	De-shuttering	1	1	1	1.00	1	11.2.3
11.3	Slab						
11.3.1	Shuttering	2	2	1	1.83	3	11.1.4
11.3.2	Steel fixing	2	1	1	1.17	3	11.3.1
11.3.3	Concrete pouring	1	1	1	1.00	1	11.3.2
11.3.4	De-shuttering	2	1	1	1.17	2	11.3.3
11.4	Stair						
11.4.1	Shuttering	1	1	1	1.00	1	11.3.1
11.4.2	Steel fixing	1	1	1	1.00	1	11.4.1
11.4.3	Concrete pouring	1	1	1	1.00	1	11.3.2
11.4.4	De-shuttering	1	1	1	1.00	1	11.4.3
Total Duration		23	18	16	18.50	19	

After completing the integration of the activities related to each floor into one package to facilitate work on them, all packages are placed in one table called project activities.

5.2. Applying CPM Method

After merging the project activities, the dependencies between the work packages are identified. The time required for each package is calculated by defining the completion time as pessimistic and optimistic, and the most likely completion time from the tables given in the previous section. For each work package of the project, PERT equation given in section 4.4.2 is used to compute the duration with three estimates. The resulting times are rounded to one integer number for the ease of computation. Table 5.10 shows the estimated times and the predecessors for each work package in the project that will be used for Network Diagraming and the following calculations for completion times and the Project buffer. The project consists of 29 work packages from start to finish.

Table 5.10. Work Packages for Project Schedule

No	Work package name	Predecessors	t_p	t_m	t_o	t_e	t
1	**Start**	-	0	0	0	0	0
2	Fences and office	1	2	1	1	1.16	2
3	Base construction	2	56	40	28	40.66	41
4	Parking floors structure work	3	126	96	66	96	96
5	Basement structure work	4	32	24	19	24.5	25
6	Ground structure work	5	31	23	18	23.5	24
7	Mezzanine structure work	6	25	19	17	19.67	20
8	Typical floors structure work	7	170	105	95	114.16	115
9	Six floor structure work	8	26	19	16	19.66	20
10	Seven floor structure work	9	25	19	17	19.67	20
11	Roof floor structure work	10	23	18	16	18.5	19
12	Epoxy for Parking	4	35	31	26	30.83	31
13	Screed for Parking	12	24	21	17	20.83	21

14	Block work	11	52	44	36	44	44
15	Plastering works	14	59	46	39	47	47
16	Tiles works	15	60	51	42	51	51
17	Building stone	15	45	38	33	38.33	39
18	Doors	16	36	30	23	29.83	30
19	Cartins wall	16	55	47	39	47	47
20	Glass wall	24	9	6	4	6.16	7
21	Truss wall	27	4	3	2	3	3
22	Railing	21	15	13	10	12.83	13
23	Installing stone	15	38	35	32	35	35
24	Gypsum	16	16	13	11	13.16	14
25	Windows marble	17	38	31	23	30.83	31
26	Windows	25	48	40	33	40.16	41
27	Painting works	16	52	43	36	43.33	44
28	Stairs marble	27	58	47	40	47.66	48
29	Finish	13,18,19,20,22,23,26,28	0	0	0	0	0

5.2.1. Network Diagram and the Critical Path

The project network diagram is drawn using the MS Project program, taking into account the relationships between activities as shown in the figure 5-1.

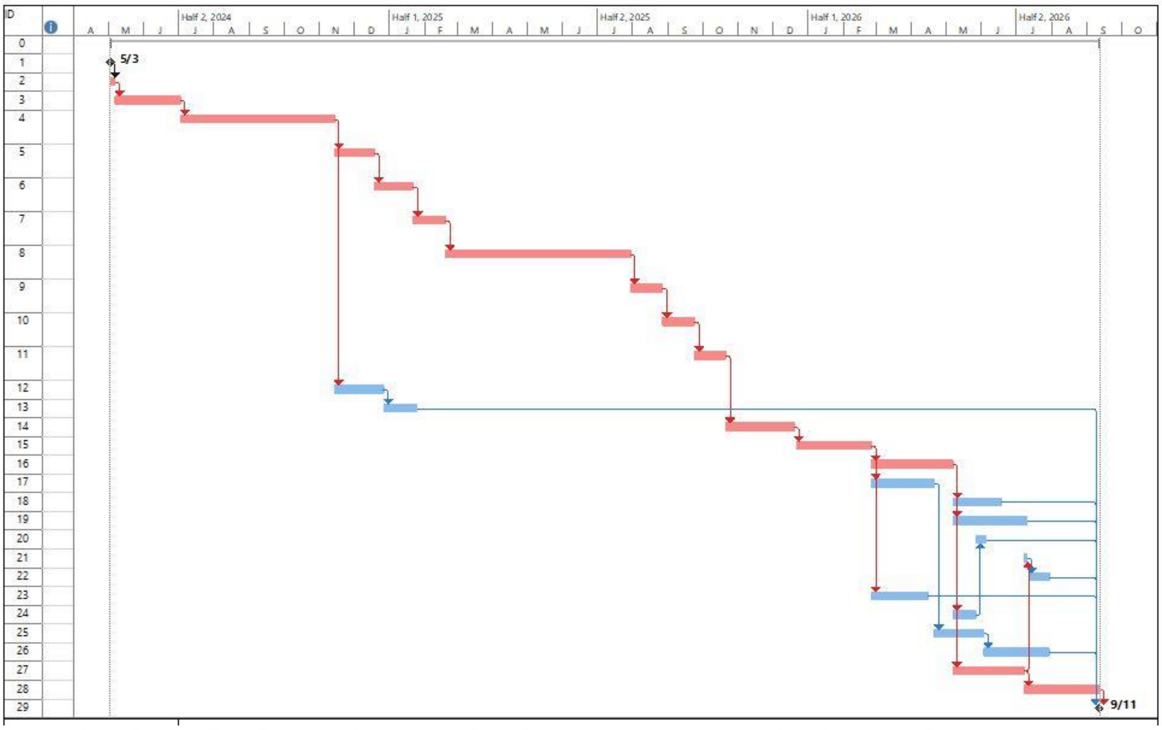

Figure 5-1. Network diagram and the critical path

The critical path is also given by the MS Project program. Table 5.11 shows the critical activities marked "yes" and the non-critical activities marked "no."

Table 5.11. Critical activities

No	Work package name	Critical
1	Start	Yes
2	Fences and office	Yes
3	Base construction	Yes
4	Parking floors structure work	Yes
5	Basement structure work	Yes
6	Ground structure work	Yes
7	Mezzanine structure work	Yes

8	Typical floors structure work	Yes
9	Six floor structure work	Yes
10	Seven floor structure work	Yes
11	Roof floor structure work	Yes
12	Epoxy for Parking	No
13	Screed for Parking	No
14	Block work	Yes
15	Plastering works	Yes
16	Tiles works	Yes
17	Building stone	No
18	Doors	No
19	Cartins wall	No
20	Glass wall	No
21	Truss wall	No
22	Railing	No
23	Installing stone	No
24	Gypsum	No
25	Windows marble	No
26	Windows	No
27	Painting works	Yes
28	Stairs marble	Yes
29	Finish	Yes

In the figure 5.1 above, which is the Gantt chart view taken from MS Project software, the critical path is shown in red, and non-critical activities are in blue.

CPM implementation revealed that the total time required to complete the project is 616 work days.

5.2.2. Resource leveled CPM analysis

Project planning using CPM is not accurate for such projects since it is independent of resources. Some tasks differ from others in relation to the number of workers. To know the true effects of the resources allocated to all activities, the number of workers in the project is also determined. It's recorded that 18 workers are assigned for this project. Table 5.12 shows the number of workers needed for each project activity together with the costs of each work package.

Table 5.12. Resources of Project's Activities

No	Work package name	Number of workers	Total Cost ($)
1	**Start**	0	0
2	Fences and office	3	4000
3	Base construction	23	98,400
4	Parking floors structure work	20	187,584
5	Basement structure work	19	44,000
6	Ground structure work	18	42,096
7	Mezzanine structure work	18	31,760
8	Typical floors structure work	16	146,050
9	Six floor structure work	15	21,020
10	Seven floor structure work	15	18,140
11	Roof floor structure work	13	9690
12	Epoxy for Parking	8	36,115
13	Screed for Parking	6	36,330
14	Block work	6	64,240
15	Plastering works	7	249,570

16	Tiles works	4	189,210
17	Building stone	4	89,349
18	Doors	4	84,120
19	Cartins wall	3	171,644
20	Glass wall	2	7000
21	Truss wall	2	18,690
22	Railing	3	8320
23	Installing stone	2	41,475
24	Gypsum	8	84,280
25	Windows marble	4	9600
26	Windows	5	73,160
27	Painting works	12	148,830
28	Stairs marble	3	10,560
29	Finish	0	0

The necessary resources are allocated to each activity, which is the number of workers, which shows a new plan for the project as shown in the figure 5-2. Resource leveling is implemented with the same software and with the resource leveled network as given in Figure 5-2. The time required to complete the project became 669 days, while it was only 616 days.

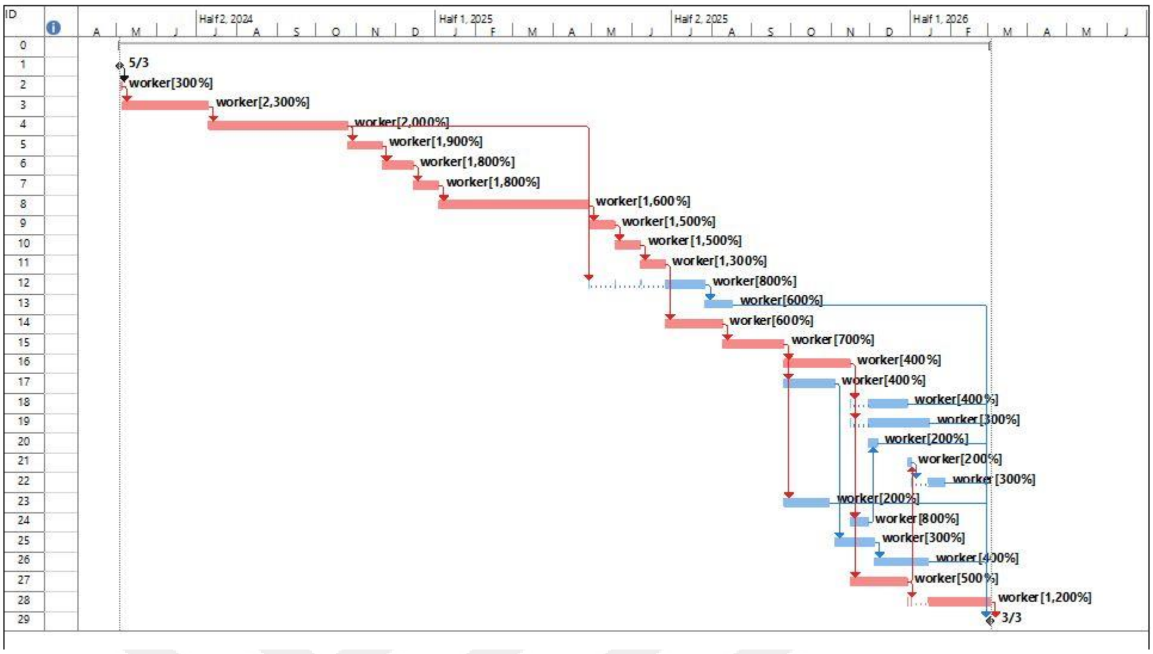

Figure 5-2. Resources levelled project network

5.3. Applying CCPM Method

The contribution of CCPM to Project scheduling is applying tighter duration estimates to the schedule. As the resource leveled network presented in the previous sections shows a long time (ie.669 days), this is not acceptable by the project owners. The maximum time expected to complete the project is maximum 2 years which gives maximum 550 work days.

Hence, the CCPM approach is suitable here to decrease the activity duration to shorter estimates in order to shorten the project completion. In this study, two approaches are examined for decreasing the task durations. First approach is using the most likely ($t=t_m$) estimates. The results of this network is given in Figure 5-3 that provides 648 work days for completing the project. That is still longer than the objective completion time. The time required to complete the project according to the most likely time method is very close to the time required to complete the project according to the CPM method, so the time will be calculated in another way. Hence the second approach is applied using half of the pessimistic duration estimates ($t=t_p/2$). The network diagram provided 433 days with this approach as shown in Figure 5-4. Although this tight schedule seems to be acceptable, it does not contain any security for unexpected problems. CCPM offers buffers for this problem. The following sections will provide the calculation of Project Buffer (PB) with different approaches in order to find the optimum buffer size and the resulting completion time for the project.In the following chapters base completion time will be taken as 433 days (CT_0 = 433 day), and the alternative Project Buffers will be added to this base completion time.

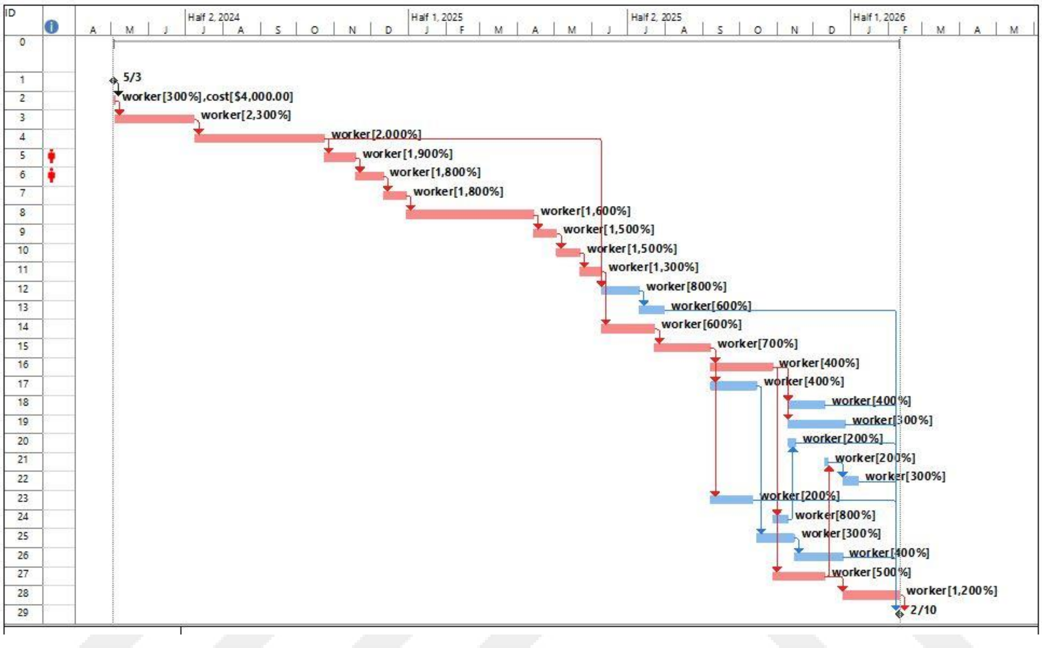

Figure 5-3 Network diagram using t_m estimates.

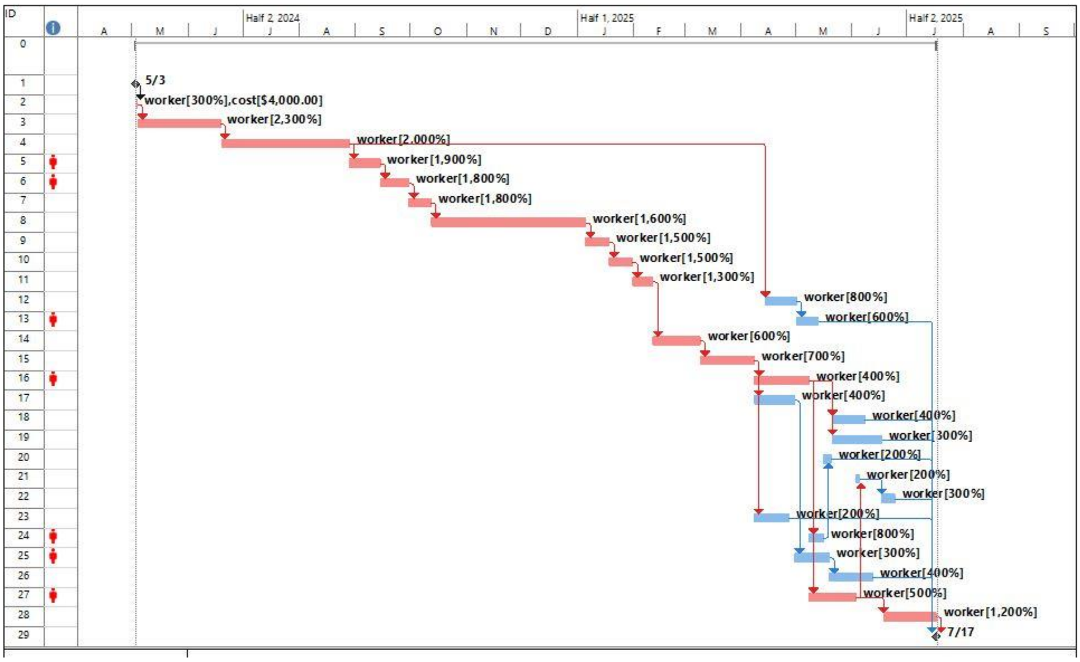

Figure 5-4. Network diagram using $t_p/2$ time estimate.

5.4. Computing Alternative Buffer Sizes and Completion Times

This section includes 4 different approaches for calculating the project buffer *(PB)* size and the consequent completion time for the project *(CT)*.

5.4.1. Calculating with SSQ Method

Calculating the Project Buffer with Square Root of Sum of the Squares (SSQ) method is based on critical activities only. The time is calculated by the difference between the pessimistic time *(t_e)* and the most likely time *(t_m)* and then applying the buffer equation to this method.

$$PB_{SSQ}=\sqrt{\sum D_i^2}$$

$$D_i = t_{pi} - t_{mi}$$

Where:

PB_{SSQ}= Project Buffer size (duration) via SSQ method

D_i = the amount of shortened duration of an activity i on the critical chain

t_{pi} = Pessimistic time of activity i on the critical chain

t_{mi} = Most likely time of activity i on the critical chain

The completion time (CT_{SSQ}) will be;

$$CT_{SSQ} = CT_0+PB_{SSQ}$$

Table 5.13 provides the D values for work packages which calculated from previous equation.

Table 5.13.Project Work packages for CCPM duration

No	Work package name	t_p	t_m	D
1	**Start**	0	0	
2	Fences and office	2	1	1
3	Base construction	56	40	16
4	Parking floors structure work	126	96	30

5	Basement structure work	32	24	8
6	Ground structure work	31	23	8
7	Mezzanine structure work	25	19	6
8	Typical floors structure work	170	105	65
9	Six floor structure work	26	19	7
10	Seven floor structure work	25	19	6
11	Roof floor structure work	23	18	5
12	Epoxy for Parking	35	31	4
13	Screed for Parking	24	21	3
14	Block work	52	44	8
15	Plastering works	59	46	13
16	Tiles works	60	51	9
17	Building stone	45	38	7
18	Doors	36	30	6
19	Cartins wall	55	47	8
20	Glass wall	9	6	3
21	Truss wall	4	3	1
22	Railing	15	13	2
23	Installing stone	38	35	3
24	Gypsum	16	13	3
25	Windows marble	38	31	7
26	Windows	48	40	8
27	Painting works	52	43	9
28	Stairs marble	58	47	11
29	Finish	0	0	0

Implementation:

The critical chain is: Start-1-2-3-4-5-6-7-8-9-10-11-14-15-16-27-28-29-finish; the project buffer is calculated as follows:

$PB_{SSQ} = \sqrt{\sum D_i^2}$

$= \sqrt{D_1^2 + D_2^2 + D_3^2 + D_4^2 + D_5^2 + D_6^2 + D_7^2 + D_8^2 + D_9^2 + D_{10}^2 + D_{11}^2 + D_{14}^2 + D_{15}^2 + D_{16}^2 + D_{27}^2 + D_{28}^2 + D_{29}^2}$

$= \sqrt{0^2 + 1^2 + 16^2 + 30^2 + 8^2 + 8^2 + 6^2 + 65^2 + 7^2 + 6^2 + 5^2 + 8^2 + 13^2 + 9^2 + 9^2 + 11^2 + 0^0}$

= 78.56 days

So, $CT_{SSQ} = CT_0 + PB_{SSQ}$

= 433 + 78.56 = 511.56 days, (approximately 512 days).

5.4.2. Calculating with APD Method

Adaptive Procedure with Density (APD) method is based on network complexity "density", by the number of predecessors present in critical activities.

PB_{APD}= K x PB_{SSQ}

NC = TOTPRE/NUMTASK

K = 1 + NC

Where:

PB_{SSQ}= Project Buffer size (duration) via SSQ method

PB_{APD}= Project Buffer size (duration) via APD method

NC = Network complexity

TOTPRE = the total number of precedence relationships defined on the sub-network feeding into the critical chain.

NUMTASK = the total number of tasks on the sub-network.

K= calculated factor

The completion time (CT_{APD}) will be;

$CT_{APD} = CT_0 + PB_{APD}$

Implementation:

NC= $\frac{16}{29}$ = 0.55

K=1+NC

= 1+0.55 = 1.55

PB_{APD} = K*PB_{SSQ}

= 1.55*78.56

= 121.8

CT_{APD} = CT_0+PB_{APD}

= 433 + 121.8 = 554.8. (Approximately 555 days).

5.4.3. Calculating with APRT Method

Adaptive Procedure with Resource Tightness method depends on the resources available in the project, including workers, costs, and materials needed to implement the project. The number of workers and the cost of the project will be used as basic sources for working on this theory. After completing the definition of the project activities and the time frame for implementation, the number of workers and the cost required for each project activity are calculated.

PB_{APRT}= K x PB_{SSQ}

RF (q) = $\frac{\sum_{i=1}^{\#critical\ activities}(Total\ number\ of\ workers\ on\ activity\ i*t_i)}{\mathrm{CT_0}*Total\ number\ of\ workers\ on\ the\ project}$

Max RF (q) = ŕ

K = 1 + ŕ

Where:

RF = Resource utilization factor.

t_i= Duration for activity i.

K= calculated factor

ŕ = resource usage

The completion time (CT_{APRT}) will be;

$CT_{APRT} = CT_0 + PB_{APRT}$

Table 5.14 shows the resources used in the project, which include Workers and cost. This table represent the number of workers for each activity and the total cost.

Table 5.14. Work and cost resources

No	Work Package name	Number of workers	t	Total number of workers	Cost per day	Total cost $
1	Start	0	0	0	0	0
2	Fences and office	3	2	6	2000	4000
3	Base construction	23	41	943	2400	98400
4	Parking floors structure work	20	96	1920	1954	187584
5	Basement structure work	19	25	475	1760	44000
6	Ground structure work	18	24	432	1754	42096
7	Mezzanine structure work	18	20	360	1588	31760
8	Typical floors structure work	16	115	1840	1270	146050
9	Six floor structure work	15	20	300	1051	21020
10	Seven floor structure work	15	20	300	907	18140
11	Roof floor structure work	13	19	247	510	9690
12	Epoxy for Parking	8	31	248	1165	36115
13	Screed for Parking	6	21	126	1730	36330
14	Block work	6	44	264	1460	64240
15	Plastering works	7	47	329	5310	249570
16	Tiles works	4	51	204	3710	189210
17	Building stone	4	39	156	2291	89349
18	Doors	4	30	120	2804	84120
19	Cartins wall	3	47	141	3652	171644
20	Glass wall	2	7	14	1000	7000
21	Truss wall	2	3	6	6230	18690
22	Railing	3	13	39	640	8320
23	Installing stone	2	35	70	1185	41475
24	Gypsum	8	14	112	6020	84280

25	Window marble	3	48	144	200	9600
26	Windows	4	31	124	2360	73160
27	Painting works	5	41	205	3630	148830
28	Stairs marble	12	44	528	240	10560
29	Finish	0	0	0	0	0
Total		243		9653		1925233

Implementation:

Resources types in the project:

q_1= Workers

q_2= Money

RF (q_1) = $\frac{\sum_{i=1}^{17}(Total\ number\ of\ project\ i * t_i}{\mathrm{CT}_0 * Total\ number\ of\ workers\ on\ the\ project}$

Total number of workers on the project = 18 worker.

RF (q_1) = $\frac{\sum 0+6+943+1920+475+432+360+1840+300+300+247+264+329+204+528+144+0}{433*18}$

RF (q_1) =1.064

RF (q_2) = $\frac{\sum_{i=1}^{17}(Money\ for\ project\ i * d_i}{\mathrm{CT}_0 * Total\ Budget}$

RF (q_2) = $\frac{\sum 0+4000+98400+187584+44000+42096+31760+146050+21020+18140+9690+64240+249570+189210+10560+9600+0}{433*1925233}$

RF (q_2) = 0.0013

Max RF (q) = ŕ

∴ ŕ = 1.064

K = 1+ 1.064

= 2.064

PB_{APRT} = K * PB_{SSQ}

PB_{APRT} = 2.064 * 78.56 = 162.15

CT_{APRT} = CT_0+PB_{APRT}

= 433 + 162.15

= 595.15 (Approximately 596 days).

5.4.4. Calculating with RD Method

Relative dispersion method in Critical Chain Project Management (CCPM) relies on assessing the variability of task durations relative to their mean or average duration. The exponent is calculated through the optimistic and pessimistic times in the project, as shown in the table 5.15 below, and through the following equations:

Table 5.15 Variance for activities.

No	**Work package name**	t_p	t_o	**Variance**
1	Start	0	0	**0.00**
2	Fences and office	2	1	**0.03**
3	Base construction	56	28	**21.78**
4	Parking floors structure work	126	66	**100.00**
5	Basement structure work	32	19	**4.69**
6	Ground structure work	31	18	**4.69**
7	Mezzanine structure work	25	17	**1.78**
8	Typical floors structure work	170	95	**156.25**
9	Six floor structure work	26	16	**2.78**
10	Seven floor structure work	25	17	**1.78**
11	Roof floor structure work	23	16	**1.36**
12	Epoxy for Parking	35	26	2.25
13	Screed for Parking	24	17	1.36
14	Block work	52	36	**7.11**
15	Plastering works	59	39	**11.11**
16	Tiles works	60	42	**9.00**
17	Building stone	45	33	4.00
18	Doors	36	23	4.69

19	Cartins wall	55	39	7.11
20	Glass wall	9	4	0.69
21	Truss wall	4	2	0.11
22	Railing	15	10	0.69
23	Installing stone	38	32	1.00
24	Gypsum	16	11	0.69
25	Windows marble	38	23	6.25
26	Windows	48	33	6.25
27	Painting works	52	36	**7.11**
28	Stairs marble	58	40	**9.00**
29	Finish	0	0	**0.00**
	Total variance for critical chain			**338.47**
	Standard deviation for project			**18.4**

$\sigma_i{}^2 = (\frac{t_P - t_O}{6})^2$

$\sigma_p = \sqrt[2]{\sum \sigma_{i\ critical}{}^2}$

$RD = \frac{\sigma_p}{CT_0}$

PB_{RD} = K x PB_{SSQ}

Where

RD = Relative dispersion

$\sigma_i{}^2$ = Variance of activity i

σ_p = Standard deviation of the project

t_o = Optimistic time

t_p = Pessimistic time

K is a safety factor added to PB_{SSQ} as Goldratt's method and selected from table 5.16 which divide the uncertainty to four classes:

Table 5-16. K factor for different classes of uncertainty

	Low safety	Median safety	High safety
A (Very Low)	4%	8%	12%
B (Low)	12%	24%	36%
C (High)	20%	40%	60%
D (Very High)	28%	57%	85%

The completion time (CT_{RD}) will be;

CT_{RD} = CT_0+PB_{RD}

Implementation:

Standard deviation of the project is calculated as 18.4 days. Hence the Relative Dispersion is computed as 0.04 giving the Very Low Uncertainty Class A (Yao & Shou, 2000).

RD = $\frac{18.4}{433}$ = 0.04

PB_{RD} = K * PB_{SSQ}

From this table, low, median and high safety levels are all applied as different scenarios for project buffer.

CT_{RD}= CT_0+ PB_{RD} = 433+ 0.04*433 = 450.32 day
CT_{RD}= CT_0+ PB_{RD} = 433+ 0.08*433 = 467.64 day
CT_{RD}= CT_0+ PB_{RD} = 433+ 0.12*433 = 484.96day

Table 5-17. PB and CT Results for RD Method

Safety Level	$\boldsymbol{PB_{RD}}$	$\boldsymbol{CT_{RD}}$
Low safety 4%	17.32	450.32
Median safety 8%:	34.64	467.64
High safety 12%	51.96	484.96

5.4.5. Combination of RD method with other methods

Different from other methods, RD approach just considers the uncertainty of activities. Hence at the final stage RD method is combined with other 3 methods. The results are provided under the following tables and the computations are provided below the tables;

Table 5-18. Results for RD (Low safety 4%) combined with other methods

Method	PB	CT
RD	17.32	450.32
SSQ & RD	81.70	514.70
APD & RD	126.67	559.67
APRT & RD	168.64	601.64

CT_{RD}= CT_0+ PB = 433+ 0.04*433 = 450.32 day

K = 1+0.04 = 1.04

PB_{SSQ_RD} = K * PB_{SSQ}

PB_{SSQ_RD} = 1.04* 78.56 = 81.7

CT_{SSQ_RD} = CT_0+PB_{SSQ_RD}

CT_{SSQ_RD} = 433 + 81.7 = 514.7 (Approximately 515 days).

PB_{APD_RD} = K * PB_{APD}

PB_{APD_RD} = 1.04* 121.8 = 126.67

CT_{APD_RD} = CT_0+PB_{APD_RD}

CT_{APD_RD} = 433 + 126.67 = 559.67 (Approximately 560 days).

PB_{APRT_RD} = K * PB_{APRT}

PB_{APRT_RD} = 1.04* 162.15 = 168.64

CT_{APRT_RD} = CT_0+PB_{APRT_RD}

CT_{APRT_RD} = 433 + 168.64 = 601.64 (Approximately 602 days).

Table 5-19. Results for RD (Medium safety 8%) combined with other methods

Method	PB	CT
RD	34.64	467.64
SSQ & RD	84.84	517.84
APD & RD	131.54	564.54
APRT & RD	175.12	608.12

CT_{RD}= CT_0+ PB = 433+ 0.08*433 = 467.64 day

K = 1+0.08 = 1.08

PB_{SSQ_RD} = K * PB_{SSQ}

PB_{SSQ_RD} = 1.08* 78.56 = 84.84

CT_{SSQ_RD} = CT_0+PB_{SSQ_RD}

CT_{SSQ_RD} = 433 + 84.84 = 517.84 (Approximately 518 days).

PB_{APD_RD} = K * PB_{APD}

PB_{APD_RD} = 1.08* 121.8 = 131.54

CT_{APD_RD} = CT_0+PB_{APD_RD}

CT_{APD_RD} = 433 + 131.54= 564.54 (Approximately 565 days).

PB_{APRT_RD} = K * PB_{APRT}

PB_{APRT_RD} = 1.08* 162.15 = 175.12

CT_{APRT_RD} = CT_0+PB_{APRT_RD}

CT_{APRT_RD} = 433 + 175.12 = 608.12 (Approximately 609 days).

Table 5-20. Results for RD (High safety 12%) combined with other methods

Method	PB	CT
RD	51.96	484.96
SSQ & RD	87.99	520.99
APD & RD	136.4	569.4
APRT & RD	181.8	614.8

CT_{RD}= CT_0+ PB = 433+ 0.12*433 = 484.96 day

K = 1+0.12 = 1.12

PB_{SSQ_RD} = K * PB_{SSQ}

PB_{SSQ_RD} = 1.12* 78.56 = 87.99

CT_{SSQ_RD} = CT_0+PB_{SSQ_RD}

CT_{SSQ_RD} = 433 + 87.99 = 520.99 (Approximately 521 days).

PB_{APD_RD} = K * PB_{APD}

PB_{APD_RD} = 1.12* 121.8 = 136.4

CT_{APD_RD} = CT_0+PB_{APD_RD}

CT_{APD_RD} = 433 + 136.4 = 569.4 (Approximately 570 days).

PB_{APRT_RD} = K * PB_{APRT}

PB_{APRT_RD} = 1.12* 162.15 = 181.8

CT_{APRT_RD} = CT_0+PB_{APRT_RD}

CT_{APRT_RD} = 433 + 181.8 = 614.8 (Approximately 615 days).

Table 5.21 shows all result of the completion time for project with different methodologies and approaches.

Table 5.21. All Results

Method	Project Buffer (days)	Completion Time (days)
CPM	-	616
CPM "resources leveled"	-	669
CCPM (t=b/2; levelled but no buffers)	-	433
Project Buffer added with SSQ Method	79.00	512
Project Buffer added with APD Method	122.00	555
Project Buffer added with APRT Method	162.00	595
Project Buffer added with RD Method using 4% safety	17.32	450.32
Project Buffer added with SSQ&RD using 4% safety	81.70	514.70
Project Buffer added with APD & RD using 4% safety	126.67	559.67
Project Buffer added with APRT & RD using 4% safety	168.64	601.64
Project Buffer added with RD using 8% safety	34.64	467.64
Project Buffer added with SSQ & RD using 8% safety	84.84	517.84
Project Buffer added with APD & RD using 8% safety	131.54	564.54
Project Buffer added with APRT & RD using 8% safety	175.12	608.12
Project Buffer added with RD using 12% safety	51.96	484.96
Project Buffer added with SSQ & RD using 12% safety	87.99	520.99
Project Buffer added with APD & RD using 12% safety	136.40	569.4
Project Buffer added with APRT & RD using 12% safety	181.80	614.8

5.5. Comparative Results and Discussion

In the case study, three solutions were used to find the time needed for the project, namely CPM with no resources, CPM with resources and the last CCPM Method.

In the first case, the time required to complete the project was 616 days, but this number is not real, as it does not depend on any resources in the project nor any risks and delays, while in the second case, the resources in the project were relied upon, which led to the completion of the project within 669 days (8% more longer duration). While in the third case, applying CCPM led to 433 days (35% less time than CPM levelling resources) without adding the Buffers that were calculated through 4 theories mentioned previously.

After applying the principle of CCPM method, and from the result in Table 5-21, there is no solution that satisfies the aim of completing the project in less than540 days (The target given by the project owners), since the results that give durations less than 540 does not satisfy the constraint which is “Project Buffer should be greater than 25%” of the length of the critical chain.

Hence, the best choice for project duration is APD approach that gives a total completion time of 555 days (114 days _17% less time than CPM levelling resources), and the buffer is 28.13% of the total length of the critical chain, so that the time required to complete the project does not exceed two calendar years. On the other hand, APD & RD with 4% safety can also be a feasible solution as it also introduces the uncertainty to the project. Minimum safety can be chosen based on the fact that construction projects are less open to unexpected risks basically thanks to their long duration. According to the result of APD & RD with 4% safety, the duration to complete the project is 560 (109 days - 16.3% less time than CPM levelling resources), and the buffer is 29.25% of the total length of the critical chain. Though not less than 540 days, so that the time required to complete the project still does not exceed two calendar years.

Comparative results are summarized in Table 5-22 that is giving the analysis of Project Buffers, their percentage relative to the length of the critical chain and the total completion time of the project when the computed buffers are added. Also Figure 5.5 displays the total completion time with a graphical perspective. Red bars are the completion times that are not applicable, and the blue bars display the comparative results. It is observed from the figure that although the methods provide longer project durations than the expected maximum (540 days asked by the project owners.), it is still satisfying the maximum of 2 years constraint.

Table 5-22. Comparative Results

Method	Project Buffer (days)	% PB/CT	Completion Time (days)
CPM	-	-	616.00
CPM "resources leveled"	-	-	669.00
CCPM (t=b/2; levelled but no buffers)	0.00	-	433.00
APRT & RD (12%)	181.80	41.99%	614.80
APRT & RD (8%)	175.12	40.44%	608.12
APRT & RD (4%)	168.64	38.95%	601.64
APRT	162.00	37.45%	595.00
APD & RD (12%)	136.40	31.5%	569.40
APD & RD (8%)	131.54	30.38%	564.54
APD & RD (4%)	**126.67**	**29.25%**	**559.67**
APD	**122.00**	**28.13%**	**555.00**
SSQ & RD (12%)	87.99	20.32%	520.99
SSQ & RD (8%)	84.84	19.59%	517.84
SSQ & RD (4%)	81.70	18.87%	514.70
SSQ	79.00	18.14%	512.00
RD (12%)	51.96	12.00%	484.96
RD (8%)	34.64	8.00%	467.64
RD (4%)	17.32	4.00%	450.32

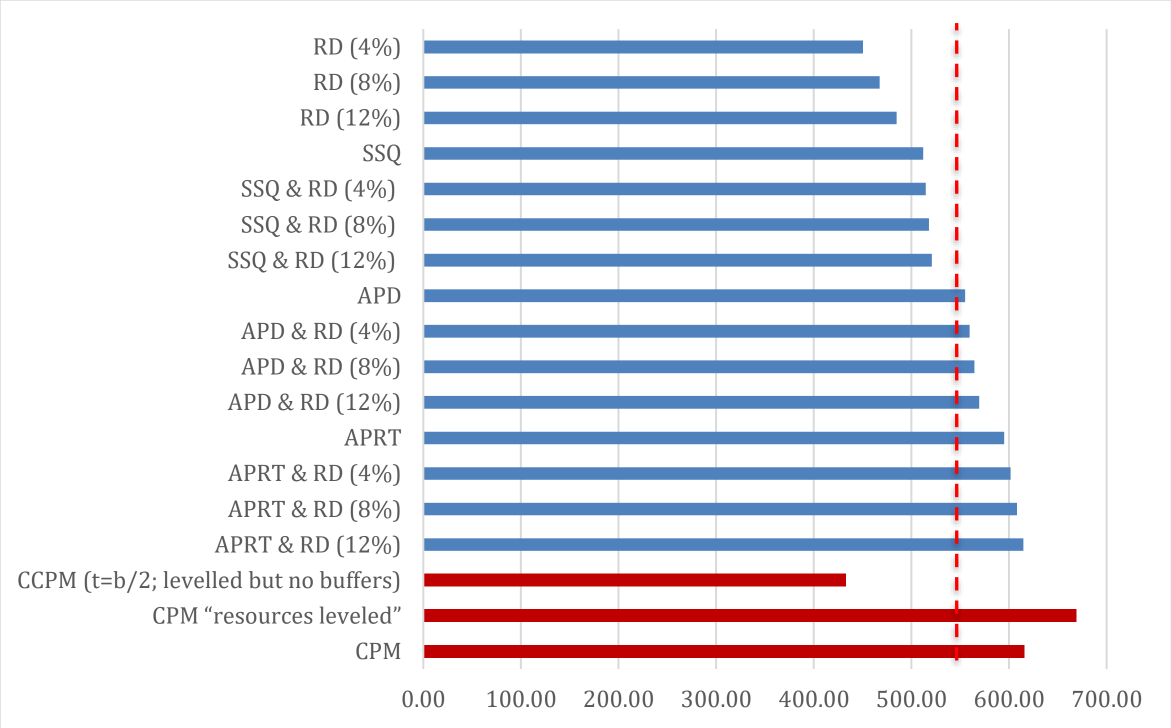

Figure 5-5.Comparative Results displayed in Bar Chart

6. CONCLUSION

This study discussed project scheduling and planning through the use of two basic methods, namely critical path method (CPM) and critical chain project management (CCPM), which were used for the same project. This study shed light on a commercial center located in Palestine that has limited resources and therefore will be relied upon in scheduling activities without multiple tasks and implementation times.

The study was based on comparing CPM and CCPM in terms of accuracy of work and implementation and in terms of their closeness to operational reality and finding the best results through these theories. At the beginning of the research, the general information of the theories was discussed through reviewing the literature and the historical overview of these theories. Then the methodology used for each theory was developed and detailed. In terms of its working mechanism and steps. In the end, these theories were applied to the data obtained from the project owners to find the necessary results in terms of the cost and estimated time of the project.

The comparison between the two methods was made through projects that depend mainly on resources, such as commercial center projects. Applying CPM to the project led to an inaccurate and ineffective result in terms of implementation, as many oppositions appeared between activities during implementation. When resources levelling was done to CPM activities, it resulted in a very long time to complete the project. After obtaining these unacceptable results, we resorted to using the CCPM method and trying to reach a solution to these problems. From this perspective various buffer sizing methods such as Square Root of Sum of the Squares (SSQ), Adaptive Procedure with Density (APD), Adaptive Procedure with Resource Tightness (APRT) and Relative dispersion (RD) are evaluated to discuss the most efficient alternative for the project case.

The results showed that using CPM without resources leads to completing the project in 616 days, while using CPM with resources leads to 669 days to complete the project, which is a very long time. When applying the critical chain, the time required to complete the project was 433 days, and after adding the buffers for the project through the four methods (SSQ, APD, APRT, and RD), the results showed a clear superiority of CCPM over CPM, and as a result APD and APD & RD with 4% safety method was chosen as the most suitable for use in this project.

The results showed that critical chain project management is most appropriate for use in resource-dependent projects that need an optimal time to complete the project without any delays or problems that may arise in implementation. CCPM has proven its effectiveness and quality for such commercial projects. This method improves the accuracy of planning and results in these projects.

After the results of this research are clear and the achievement achieved, several recommendations can be proposed for future research. First, the use of the critical chain method in various sectors in Palestine, such as factories and offices. Second, the possibility of using advanced technologies such as artificial intelligence and machine learning to improve the size of the buffer and accuracy in the duration of project completion. Third, the use of the critical chain in calculating the cost of engineering projects and the extent of their impact on the economy of the project.

7. References

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8. Appendix

Project Activities.xlsx