Evaluation of Project Scheduling and Control for the Construction of Four Storey Apartment Using Critical Chain Project Management (CCPM)

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Abstract. The development of the education infrastructure sector in Indonesia faces significant challenges where 78% of construction project delays are caused by student's syndrome and ineffective buffer time allocation. The Critical Path Method (CPM), which has long been the standard for construction project scheduling, has proven to be less efficient because it overlooks productivity factors, resource limitations, and human factor issues such as multitasking and Parkinson's Law, and tends to allocate excessive buffer time to each activity. This study aims to evaluate the effectiveness of the Critical Chain Project Management (CCPM) method as an alternative to the Critical Path Method (CPM) in optimizing the scheduling and control of educational facility construction projects. The research was conducted through a case study on the construction of the Muallimin Muhammadiyah Islamic Boarding School Dormitory by reorganizing the optimal schedule, performing critical chain analysis, calculating strategic buffers, and evaluating the optimized schedule and budget percentages. CCPM applies a different approach from conventional methods by eliminating contingency time on each activity and replacing it with a buffer centralized at the end of the critical path. The research results show that the implementation of CCPM successfully optimized the project schedule by reducing the duration from 240 working days to 205 working days (14.6% more efficient) through a cut and paste approach with a 50% duration reduction and the addition of an RSEM buffer. Cost efficiency of Rp 2,410,931,721.07 or equivalent to 22.12% was also achieved due to the reduction in daily labor costs. This finding proves that CCPM can overcome the weaknesses of CPM and become a superior method in handling resource conflicts and deterministic durations, thereby resulting in more optimal time planning and resource utilization for national infrastructure development.

Introduction

The development of the education infrastructure sector in Indonesia has become a major concern for the government in order to improve the quality of education facilities. Despite this, many construction projects have experienced significant time deviations [1]. Recent studies show that 78% of construction project delays in Indonesia are caused by student's syndrome and ineffective safety time allocation [2]. Islamic Boarding school Muallimin Muhammadiyah, as one of the oldest Islamic educational institutions in Indonesia, has planned to add dormitory facilities to increase the accommodation capacity for students and improve the quality of the learning environment. The Islamic Boarding plays a significant role in national education by combining strong Islamic values with a modern curriculum [3].

The Critical Path Method (CPM) has long been an accepted standard in project scheduling, particularly in the construction and manufacturing sectors. CPM provides an understanding of project completion time and the identification of the critical path. However, in practice, CPM is often considered less efficient because it does not take into account productivity factors, resource limitations, and issues caused by human factors, such as multitasking, the student syndrome phenomenon, and Parkinson's Law, which can lead to project delays. CPM also tends to allocate buffer time to each activity, causing the project completion time to be longer than it should be [4].

To address the limitations of CPM, in 1997 Eliyahu M. Goldratt introduced the Critical Chain Project Management (CCPM) method. In the CCPM method, the addition of safety time that is usually placed on each activity will be eliminated and replaced with buffer time placed at the end of the critical chain as a reserve time for the entire project. The application of the CCPM method in the construction project successfully reduced the project duration and significantly lowered labour costs [2,5]. This method can reduce waste and identify potential risks in the future, as well as calculate the optimal work time estimate [6]. Evaluating each waste and risk can influence each other, therefore planning related to the possibility of waste and risk is necessary [7].

Because of the importance of time in construction project scheduling, the choice of method used to create the schedule can determine the success of the project. In the construction of the Islamic boarding school Muallimin Muhammadiyah apartment building, the CPM method is still used, which neglects resource issues and uses individual buffers for each work item, causing the work to take longer because each task has its own safety time. Because the longer the construction project takes, the more expensive the daily costs become, ignoring resource conflicts and using deterministic durations are the main problems of the CPM method[8]. For an alternative that takes into account resource limitations and strategically adds buffers to protect the project schedule, the CCPM method becomes the right choice. In another case study, the CCPM method can produce a more efficient schedule with precise buffer calculations[4, 9,10].

This research aims to evaluate the scheduling and project control that previously used the less efficient CPM method with the CCPM method in the construction of the Muallimin Muhammadiyah Islamic Boarding School Apartment. Based on the identified issues, the author reorganized the optimal schedule, analyzed the critical chain, calculated the necessary buffers, and analyzed the percentage of the schedule and budget that had been optimized in the construction of the Muallimin Muhammadiyah Islamic Boarding School Apartment project. The results of this research are expected to contribute positively to the development of construction project management practices in Indonesia, particularly in the construction of educational facilities.

Literature Review

Construction Project Management. Project management is the process of planning, organizing, overseeing, and managing a firm's resources to attain short-term objectives, with heightened emphasis on specific goals and objectives [11]. Project management is considered the utilization of expertise, skills, resources, and methods to meet the demands of a project[12]. There are five interrelated project management activity processes, namely Project Initiation, Project Planning, Project Execution, Project Monitoring & Control, and Project Closure as shown in Figure 1.

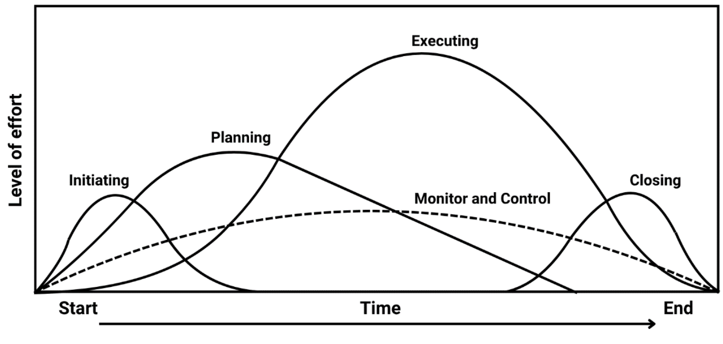

Fig. 1. The Interconnection of Project Management Activities [12]

Figure 1 illustrates the five interrelated key processes in construction project management. The Initiating phase focuses on identifying the project's needs and justifying it, demonstrated by a significant but short initial effort. The Planning phase then serves as the basis for technical and managerial planning, marked by increasing intensity of effort leading up to the implementation phase. The Executing phase, which encompasses the implementation of all planned fieldwork, continues in parallel, ensuring that any deviations from the plan are effectively controlled, particularly in terms of time, cost, and quality. At the end of the project, the Closing phase demonstrates a renewed increase in effort to complete all administrative tasks, final evaluation, and handover of work. This visualization provides a comprehensive understanding of the distribution and focus of construction project management activities from inception to completion.

Critical Path Method (CPM). The Critical Path Method (CPM) was developed by James E. Kelley Jr. of Remington Rand and Morgan R. Walker of DuPont Company in 1957 as a project scheduling approach designed to outline the tasks required to complete a project and determine flexibility in planning[13]. The CPM method is a project scheduling approach designed to outline the tasks required to complete a project and determine flexibility in planning. The CPM method utilizes network modelling to identify the critical path, a series of activities that determine the minimum duration of a project's completion. Activities on the critical path have no slack or float time, so any delay in any of these activities will directly affect the total project duration[10,11]. Although the CPM method has become the conventional standard in project scheduling, this method is deterministic and does not take into account productivity fluctuations or resource limitations that occur dynamically in the field.

Critical Chain Project Management (CCPM). Critical Chain Project Management (CCPM) was first introduced by Eliyahu M. Goldratt in 1997. This method is a project management approach that focuses on managing activity duration, taking into account resource allocation, and is developed based on the Theory of Constraints (TOC)[12,13]. This method aims to optimize resource utilization by identifying and managing the critical chain, which is the longest sequence of activities that takes into account task dependencies and resource constraints. CCPM addresses common project management issues such as student syndrome (delaying work until the deadline approaches), Parkinson's law (work expands according to the time available), and overtime protection for each task. In CCPM implementation, task duration estimates are based on reasonable times, encouraging teams to work at a normal pace without delays or saving time. Buffer management is key in the CCPM Method, where buffer consumption is monitored as an indicator of project success and a signal for corrective action if needed.

Buffer Management. In the Critical Chain Project Management (CCPM) approach, buffer management plays an important role as a barometer of project progress and an early detection tool to anticipate potential delays [17]. Project buffers are placed at the end of the critical chain to protect the overall project completion, while feeding buffers are inserted on non-critical paths to prevent disruptions from non-critical activities that could affect the main path [18].

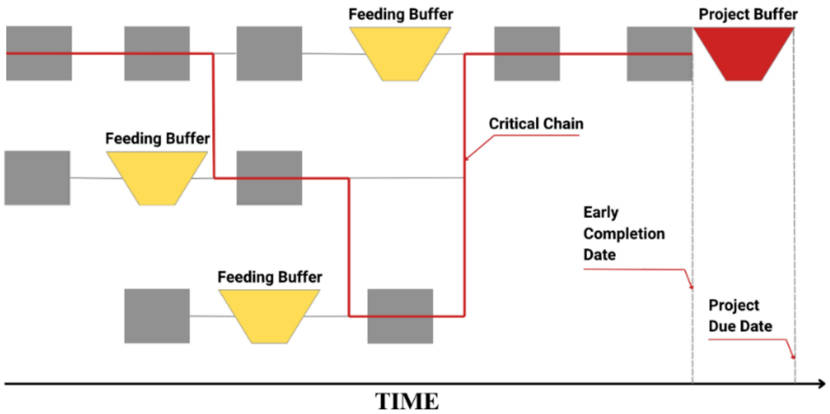

Fig. 2. Placement of Project Buffer and Feeding Buffer

The concept of buffer management in the Critical Chain Project Management (CCPM) method commonly used in construction project management can be seen in Figure 2. The red line indicates the project's critical path, called the critical chain, which is a sequence of activities that takes into account resource constraints. To anticipate uncertainty and potential delays, a feeding buffer is inserted at the intersection of the non-critical path and the critical path, functioning to protect the critical path from disruptions originating from other activities. At the end of the critical path, a project buffer is provided that acts as a time buffer between the actual completion date and the project due date. The placement of this buffer allows project managers to proactively monitor progress and take corrective actions before delays occur, thereby increasing the reliability of construction project completion times.

The buffer duration is calculated using two main methods, namely the Cut and Paste Method (C&PM) and the Root Square Error Method (RSEM) [19]. In C&PM, the allocation of buffer time is determined by trimming a portion of the safety time that has been provided for each activity, usually cut by 20%, 50%, or even up to 80%, depending on the company's experience. This approach not only provides flexibility in scheduling but also creates space for the project to remain on the optimal completion path. Here is the buffer calculation formula:

$$Buffer = 2 \times \sqrt{\left(\frac{w_1 - a_1}{2}\right)^2 + \left(\frac{w_2 - a_2}{2}\right)^2 + \dots + \left(\frac{w_n - a_n}{2}\right)^2} \,.$$

(1)

Where w is duration that has spare time and a is Duration that has not spare time. In the implementation of Critical Chain Project Management (CCPM), there are three main steps that must be observed to ensure effective project management [20]. First, identify the critical chain, which is the longest path of activities that determines the total duration of the project. Second, optimize the utilization of the critical chain by shortening the duration of each activity. Third, integrate other activities into the main schedule by inserting buffer time, which serves as a cushion to absorb uncertainty and keep the project on track. These three stages are interconnected and serve as the main foundation for maintaining the rhythm and efficiency of CCPM-based project execution.

Research Methodology

This research begins with a literature review as a problem solver and seeks supporting journals on Buffer management and Critical Chain Project Management (CCPM). The next stage is data collection in the form of administrative data, Work Breakdown Structure (WBS), budget plan, and schedule plan. Next, the data processing stage is carried out, starting with analyzing the WBS by finding and identifying the critical path. Second, analyze the buffer by reducing the total duration of each project activity to 50% of the actual time and conduct buffer analysis using the Root Square Error Method (RSEM). Next, reschedule using the CCPM method by determining key components such as feeding, resource, cost, and project buffer. The next step is to create a new schedule and calculate the project cost. Then compare the duration and cost of the old project with the results of the CCPM method. The final stage is to draw conclusions that align with the results obtained from the research.

Master Schedule. In Table 1, the master schedule shows that several key activities have an impact on the project's critical path. In the preparation work, the longest duration is 240 days, while the structural work on the second, third, and fourth floors shows the largest combination of time and cost burden, each lasting 45, 58, and 41 days with a value of more than Rp1.3 billion per floor.

Table 1. Work Breakdown Structure and Budget Plan

No	Work item	Duration (Day)	Total cost (IDR)
1	Preparation Work	240	89,747,767.60
2	RK3K Construction Work	30	114,536,959.41
3	Standard Structural Work		
3.1	First Floor Structural Work	45	824,958,387.33
3.2	Second Floor Structural Work	58	1,310,208,358.52
3.3	Third Floor Structural Work	41	1,309,293,734.89
3.4	Fourth Floor Structure Work	26	1,312,824,572.17

No	Work item	Duration (Day)	Total cost (IDR)
3.5	Roof Deck Work	28	469,395,440.70
3.7	Steel Roof Frame	14	535,104,742.70
4	Non-Standard Structural Work		
4.1	Sub Structure work	66	1,567,038,843.72
5	GWT Structure and Pump Room Work		
5.1	Pump Room Structural Work	53	60,894,646.61
5.2	Foundation Structure Work Stp		15,641,422.62
6	Standard Architecture Work		
6.1	First Floor Work	75	
6.1.1	Wall and Concrete Work		580,581,390.48
6.1.2	Door, Window + Accessories & Railing Frame Work		492,905,254.00
6.1.3	Ceiling Work		144,984,189.05
6.1.4	Floor Work		222,135,076.70
6.1.5	Utility Work		135,353,507.00
6.1.6	Painting Work		69,582,964.82
6.1.7	Ramp work at the terrace entrance, accessories on the facade, and the walkway around the building		9,956,318.34
6.2	Second Floor Work	62	
6.1.1	Wall and Concrete Work		565,018,051.33
6.1.2	Door, Window + Accessories & Railing Frame Work		362,236,970.00
6.1.3	Ceiling Work		139,447,222.38
6.1.4	Floor Work		177,443,758.30
6.1.5	Utility Work		100,513,442.00
6.1.6	Painting Work		71,071,839.03
6.3	Third Floor Work	41	
6.3.1	Wall and Concrete Work		565,958,870.53
6.3.2	Door, Window + Accessories & Railing Frame Work		129,485,207.00
6.3.3	Ceiling Work		119,920,000.38
6.3.4	Floor Work		173,669,190.20
6.3.5	Utility Work		100,513,442.00
6.3.6	Painting Work		71,071,839.03
6.4	Fourth Floor Work	36	
6.4.1	Wall and Concrete Work		426,313,665.92
6.4.2	Door, Window + Accessories & Railing Frame Work		129,485,207.00
6.4.3	Ceiling Work		97,041,449.92
6.4.4	Floor Work		131,535,933.08
6.4.5	Utility Work		100,513,442.00
6.4.6	Painting Work		53,782,864.11
6.5	Floor Slab and Roof Work	48	
6.5.1	Wall and Concrete Work		125,071,130.40
6.5.2	Door, Window + Accessories & Railing Frame Work		42,402,200.00
6.5.3	Ceiling Work		16,698,232.80
6.5.4	Floor Work		25,972,260.00
6.5.5	Utility Work		2,380,510.00
6.5.6	Painting Work		52,253,354.50
6.5.7	Roof Covering Work		379,815,029.76

Determining the Critical Path shows the sequence of activities along with the critical path, making the controlling process easier. In this scheduling, AON (Activity on Node) is used to determine the timing, which includes a forward pass consisting of early start and early finish, and a backward pass consisting of latest start and latest finish. Based on the existing schedule, the free float and total float are determined, and it can then be seen whether the task is on the critical path or not.

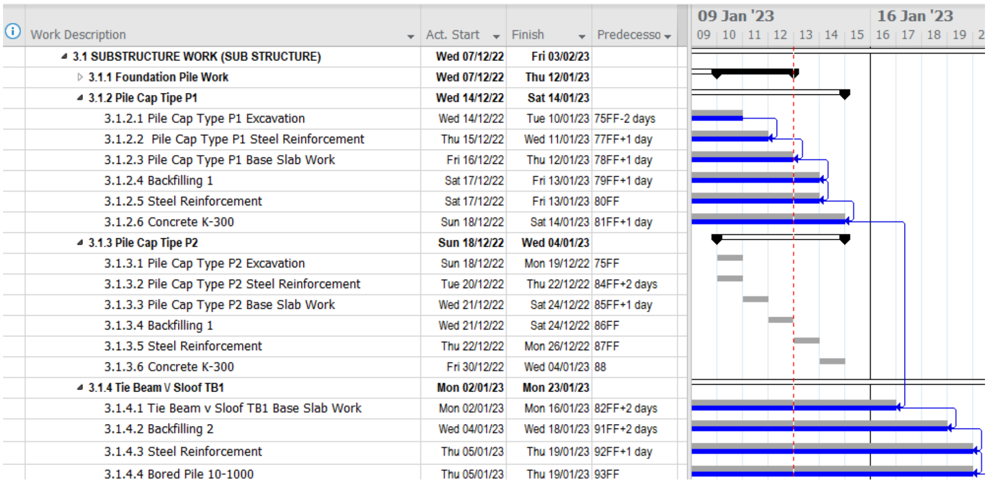

Fig. 3. Dependency Relationships in MS.Project

Figure 3 shows the original schedule data for the Muallimin Muhammadiyah Islamic Boarding School Apartments, which demonstrates the use of dependency relationships between activities in Microsoft Project, such as Finish-to-Start (FS) and Finish-to-Finish (FF), which form a sequential project workflow. In the substructure work, activities such as excavation, reinforcement, casting, and backfilling are interconnected with FS, where one job cannot begin before the previous job is completed. Some activities also use FF to align completion simultaneously. These relationships can later form a critical path in the project work, namely a series of activities with no time slack, if one is delayed it will affect the overall duration of the project.

Result and Discussion

Analysis of Critical Chain Project Management Scheduling. This research uses the CCPM method, which is employed to provide scheduling suggestions and cost savings. Based on primary data obtained from the company in Table 1.

Project Buffer and Feeding Buffer. Microsoft Project is utilized in Scheduling to calculate using the CCPM Method. The process starts by identifying the order of tasks in the project timeline. Next, the determination of critical and non-critical paths is carried out to observe the dependencies between related tasks, with the assumption that these task relationships are constraints that will affect the resources needed to complete the construction project. In Figure 4, the critical path is seen in the structural work of beams and columns on the 2nd floor. The critical path also includes the preparatory work with sub-items of water and electrical work, the structural work on the 3rd floor, the structural work on the 4th floor, the roof deck work, and the steel roof frame work.

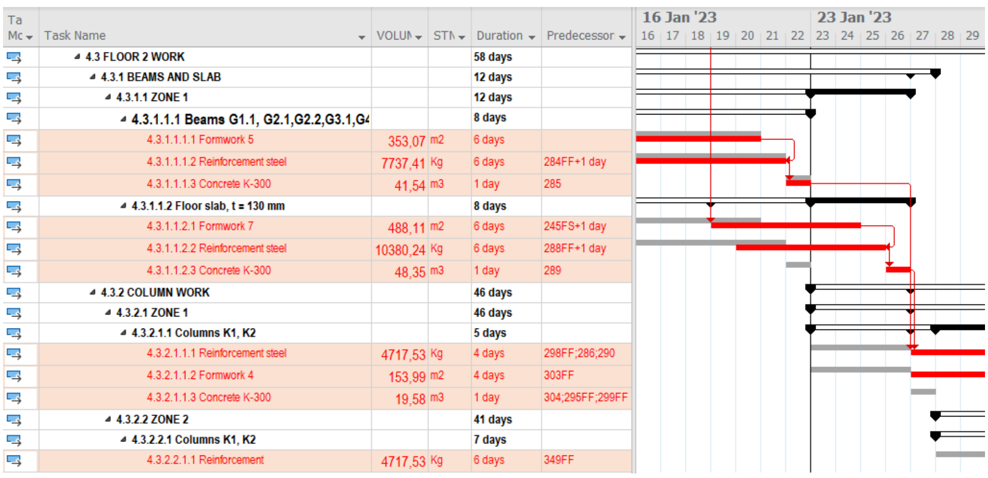

Fig. 4. Critical path of tasks in Microsoft Project

To calculate the time buffer, the duration of the work time in table 1 is reduced by 50% (Cut and Paste Method) and continued with the RSEM method calculation. The work item is divided into two calculations, namely the Project buffer which will be placed at the end of the work and the Feeding buffer which is inserted on the non-critical path to prevent disruptions that affect the main activity, as depicted in Figure 2.

Table 2. Project Buffer

No	Work item	Original Schedule /Day	Estimate Duration Critical Chain			Critical Chain Schedule
			Cut & Paste Method	$\frac{w_1-a_1}{2}$	$\left(\frac{w_1-a_1}{2}\right)^2$	
1	Preparation Work	240	120	60	3600	
2	Sub Structure Work	66	33	33	272.25	
3	GWT Structure and Pump Room Work	53	26.5	26.5	175.56	
				Project Buffer	**447.81**	**43**

Table 3. Feeding Buffer

No	Work item	Original Schedule /Day	Estimate Duration Critical Chain			Critical Chain Schedule
			Cut & Paste Method	$\frac{w_1-a_1}{2}$	$\left(\frac{w_1-a_1}{2}\right)^2$	
1	RK3K Construction Work	30	15	7.5	56.25	21
2	First Floor Structural Work	45	22.5	11.25	126.56	29
3	Second Floor Structural Work	58	29	14.5	210.25	35
4	Third Floor Structural Work	41	20.5	10.25	105.06	27
5	Fourth Floor Structure Work	26	13	6.5	42.25	19
6	Roof Deck Work	28	14	7	49	20
8	Steel Roof Frame	14	7	3.5	12.25	13
9	First Floor Work	75	37.5	18.75	351.56	44
10	Second Floor Work	62	31	15.5	240.25	37
11	Third Floor Work	41	20,5	10.25	105.06	27
12	Fourth Floor Work	36	18	9	81	24
13	Floor Slab and Roof Work	48	24	12	144	30
				Feeding Buffer	**1534.06**	**78**

From the project buffer calculation results in Table 2, a time of 43 days is obtained which will be placed at the end of the work, and the feeding buffer in Table 3 to be placed between the critical chain and the non-critical chain is 78 days. After calculating the buffers in Tables 2 and 3, the next step can be made a rescheduling using Microsoft Project as can be seen in Figure 5.

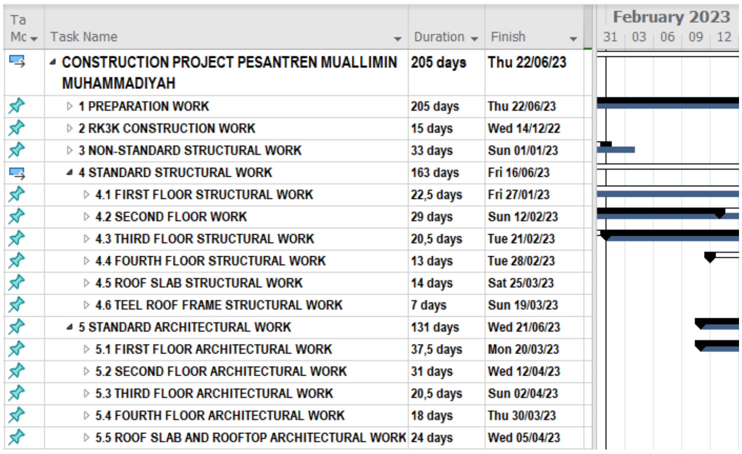

Fig. 5. Rescheduling in Microsoft Project

Table 4. Difference in project costs with CCPM

No	Work item	Cost (IDR)	
		Initial Cost	CCPM
1	Preparation Work	89,747,767.60	87,534,008.00
2	First Floor Structural Work	824,958,387.33	779,785,112.36
3	Second Floor Structural Work	1,310,208,358.52	1,259,708,225.78
4	Third Floor Structural Work	1,309,293,734.89	1,257,379,764.19
5	Fourth Floor Structure Work	1,312,824,572.17	1,258,197,192.77
6	Roof Deck Work	469,395,440.70	443,353,136.96
8	Steel Roof Frame	535,104,742.70	496,882,975.37
9	Sub Structure Work	1,567,038,843.72	1,159,234,030.50
10	GWT Structure and Pump Room Work	76,536,069.24	71,688,784.85
11	First Floor Work	1,655,498,700.39	1,385,100,579.33
12	Second Floor Work	1,415,731,283.04	1,184,495,173.48
13	Third Floor Work	1,160,618,549.15	971,050,852.79
14	Fourth Floor Work	938,672,562.04	785,356,043.58
15	Floor Slab and Roof Work	644,592,717.46	539,309,240.28
	Total cost	13,310,221,728.95	10,899,290,007.88

After the scheduling was completed, a cost difference between the CPM method and the CCPM method was produced, as shown in Table 4. The CCPM method has an efficiency of 22.12% with a total cost difference of Rp. 2,410,931,721, indicating that the implementation of CCPM significantly enhances project cost efficiency through the optimization of activity durations and the reduction of unproductive time. The time efficiency of 14.6% and cost efficiency of 22.12% are consistent with the Theory of Constraints and confirm Anastasiu's findings in the Buildings Journal, which reported a 20%-time savings in construction projects [21], Kim's findings in the International Journal of Sustainable Building Technology with 15-25% efficiency through smart buffer extraction [22], and Sembiring & Putra's findings in the IOP Conference Series, which achieved 12-18% time efficiency [10]. The strength of this research lies in the application of the 50% Cut and Paste Method, which resulted in a project buffer of 43 days and a feeding buffer of 78 days, with a conservative yet effective approach for the Indonesian construction context, as well as the validation of CCPM on Islamic education infrastructure, demonstrating that RSEM buffer calculation can accommodate the high variability of local construction projects without compromising schedule reliability.

Conclusion

Based on the analysis and discussion of the research evaluating the effectiveness of the Critical Chain Project Management (CCPM) method as an alternative to the Critical Path Method (CPM) in the construction of the Muallimin Muhammadiyah Islamic Boarding School Apartment, the following conclusions can be drawn:

1. The implementation of the CCPM method has proven to be significantly more effective compared to the conventional CPM method in optimizing construction project scheduling. The total project duration was successfully optimized from 240 working days to 205 working days, resulting in a time efficiency of 14.6%. This achievement proves that CCPM is capable of overcoming the fundamental weaknesses of CPM in handling deterministic estimates and inefficient buffer allocation.
2. The critical chain analysis in CCPM successfully identified and managed resource constraints, resulting in more optimal resource utilization and reduced waste. The use of project buffers and feeding buffers is more effective than individual CPM buffers, which cause excessive safety time for each activity.

3. The implementation of CCPM resulted in substantial cost efficiency amounting to Rp2,410,931,721.07 or equivalent to 22.12% of the total project budget, reducing costs from Rp13,310,221,728.95 to Rp10,899,290,007.88. The cost reduction is sourced from the reduction in labor costs due to duration acceleration, optimization of resource utilization, and elimination of overhead costs for extended time.
4. The use of the cut and paste method with RSEM can develop a practical application method for buffer calculation in the Theory of Constraints (TOC) within the context of construction in Indonesia, and this research fills the gap as a comprehensive study analysing CCPM in Islamic education infrastructure.
5. The CCPM method can be a broad strategic choice for the Indonesian construction industry, particularly in addressing project delays that reach 78%. CCPM has the potential to become a new standard for improving time and cost efficiency.
6. CCPM has proven effective in reducing the influence of factors such as student's syndrome, multitasking, and Parkinson's Law, which cannot be addressed by the CPM method. However, successful implementation requires a strict monitoring system and measured buffer management to ensure realization according to plan.
7. The limitation in this study lies in the single case study, which reduces the ability to generalize the findings to other construction projects with different characteristics. Therefore, subsequent research is recommended to adopt a multiple case study approach on various types of construction projects, comparative analysis on projects with different scales and complexities, and development to analyse the long-term application of CCPM.

References

[1] M. Aman and J. Siregar, ‘Analisis Deviasi Kemajuan Pekerjaan Berdasarkan Persentase Durasi Waktu Pada Pekerjaan Konstruksi Bangunan’, *Menara: Jurnal Teknik Sipil*, vol. 18, no. 1, pp. 59–65, Jan. 2023, doi: 10.21009/jmenara.v18i1.29213.

[2] U. D. Tampubolon, T. Rahman, and B. Haryanto, ‘Evaluasi Penjadwalan Proyek Konstruksi dengan Metode Critical Chain Project Management (CCPM) (Studi Kasus: Proyek Pembangunan Pengganti dan Fasilitas di Yonif 661/AWL Kompi Senapan Samarinda)’, *Teknologi Sipil*, vol. 5, no. 1, pp. 30–43, 2021.

[3] N. M. Awwaliyah, ‘Pondok Pesantren Sebagai Wadah Moderasi Islam Di Era Generasi Millenial’, *Islamic Review : Jurnal Riset dan Kajian Keislaman*, vol. 8, no. 1, pp. 36–62, Apr. 2019, doi: 10.35878/islamicreview.v8i1.161.

[4] M. F. N. Aulady and C. Orleans, ‘Perbandingan Durasi Waktu Proyek Konstruksi Antara Metode Critical Path Method (CPM) dengan Metode Critical Chain Project Management (Studi Kasus: Proyek Pembangunan Apartamen Menara Rungkut)’, *Jurnal IPTEK*, vol. 20, no. 1, p. 13, Jun. 2016, doi: 10.31284/j.iptek.2016.v20i1.29.

[5] S. Sugiyanto and K. Insan, ‘Penerepan Optimalisasi Metode Critical Chain Project Management Pada Pelaksanaan Proyek Kontruksi’, *Rang Teknik Journal*, vol. 5, no. 2, pp. 352–363, Jun. 2022, doi: 10.31869/rtj.v5i2.3121.

[6] F. D. Ariyanti, A. C. Putri, and D. A. Ningtyas, ‘Implementation of lean construction and critical chain project management (CCPM) for waste management and work estimation on the Ciawi dam construction project’, in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Aug. 2021. doi: 10.1088/1755-1315/794/1/012074.

[7] U. H. Issa, ‘Implementation of lean construction techniques for minimizing the risks effect on project construction time’, *Alexandria Engineering Journal*, vol. 52, no. 4, pp. 697–704, 2013, doi: 10.1016/j.aej.2013.07.003.

[8] F. Zhang, ‘A Study on Computerized Simulation of difference between CPM and CCPM’, in *Proceedings of the 2016 3rd International Conference on Materials Engineering,*

Manufacturing Technology and Control, Paris, France: Atlantis Press, 2016. doi: 10.2991/icmemtc-16.2016.83.

[9] Andiyan, R. M. Putra, G. D. Rembulan, and H. Tannady, 'Construction Project Evaluation Using CPM-Crashing, CPM-PERT and CCPM for Minimize Project Delays', in *Journal of Physics: Conference Series*, IOP Publishing Ltd, Jun. 2021. doi: 10.1088/1742-6596/1933/1/012096.

[10] N. Sembiring and A. Putra, 'Scheduling evaluation in construction projects using the critical chain project management method', in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, May 2020. doi: 10.1088/1757-899X/830/3/032091.

[11] Harold Kerzner, *Project Management: A Systems Approach To Planning, Schedule And Control*, Edisi 10. Canada: JOHN WILEY & SONS, LTD, 2009.

[12] PMBOK, *A Guide to the Project Management Body of Knowledge (PMBOK® Guide) : Seventh Edition and The Standard for Project Management*, 7th ed. Project Management Institute, Inc., 2021.

[13] J. E. Kelley and M. R. Walkerf, 'Critical-Path Planning and Scheduling', 1959.

[14] M. Shurrab, 'Traditional Critical Path Method versus Critical Chain Project Management: A Comparative View', *International Journal of Economics & Management Sciences*, vol. 04, no. 09, 2015, doi: 10.4172/2162-6359.1000292.

[15] L. P. . Leach, *Critical chain project management*. Artech House, 2000.

[16] J. H. Blackstone, J. F. Cox, and J. G. Schleier, 'A tutorial on project management from a theory of constraints perspective', *International Journal of Production Research*, vol. 47, no. 24, pp. 7029–7046, Feb. 2009, doi: 10.1080/00207540802392551.

[17] B. She, B. Chen, and N. G. Hall, 'Buffer sizing in critical chain project management by network decomposition', *Omega (United Kingdom)*, vol. 102, Jul. 2021, doi: 10.1016/j.omega.2020.102382.

[18] S. P. Sreenivas Padala, L. Divakar, and P. Vijay Kumar, 'Buffer Sizing in Construction Scheduling Using Critical Chain Project Management', in *Lecture Notes in Civil Engineering*, Springer Science and Business Media Deutschland GmbH, 2023, pp. 969–978. doi: 10.1007/978-981-19-4040-8_78.

[19] R. Sproull, *Theory of constraints, lean, and six sigma improvement methodology : making the case for integration*. Routledge, 2019.

[20] T. Sinaga and A. E. Husin, 'Analysis of time efficiency with ccpm method and bim in construction projects construction of high-rise residential building basement', *Civil Engineering and Architecture*, vol. 9, no. 5, pp. 1465–1477, Aug. 2021, doi: 10.13189/CEA.2021.090519.

[21] L. Anastasiu, C. Câmpian, and N. Roman, 'Boosting Construction Project Timeline: The Case of Critical Chain Project Management (CCPM)', *Buildings*, vol. 13, no. 5, May 2023, doi: 10.3390/buildings13051249.

[22] N. Kim, H. Moon, B. Son, and M. Park, 'Smart and robust critical chain scheduling for construction projects using buffer extraction', *International Journal of Sustainable Building Technology and Urban Development*, vol. 12, no. 4, pp. 394–409, 2021, doi: 10.22712/susb.20210032.