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Critical Chain Project Management for Hospital Reconstruction: Cost and Time Optimization

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ABSTRACT

Construction project delays represent a persistent challenge in Indonesian infrastructure development, with delay rates reaching 38% and causing substantial cost overruns and quality compromises. This research evaluated the application of Critical Chain Project Management methodology to optimize cost and time performance in the Undata Hospital Phase II-B Rehabilitation and Reconstruction Project in Palu, Central Sulawesi, which experienced significant delays from 240 contracted days to 426 actual implementation days. Using Microsoft Project for critical chain identification and Root Square Error Method for buffer calculation, the study analyzed 228 structural work activities to determine schedule optimization potential. Results identified nine critical chain activities concentrated in foundation work, requiring 60-day project buffer and 36-day feeding buffer allocation. CCPM application achieved 159-day duration reduction (43.1% improvement) compared to actual implementation, reducing total duration from 369 days to 210 days. Economic analysis revealed potential labour cost savings of IDR 7,398,931,383.36 (59.0% reduction) through elimination of embedded safety time and strategic buffer placement. Comparative evaluation demonstrated that traditional scheduling dispersed 183 days of safety time across individual activities, manifesting as work expansion through Parkinson's Law effects. Even under partial buffer consumption scenarios, CCPM maintained substantial performance advantages, confirming methodology robustness. These findings support CCPM adoption for Indonesian reconstruction projects requiring complex coordination, extended durations, and strategic schedule management under international funding frameworks.

Keywords: *Buffer Management, Construction Project Management, Cost Optimization, Critical Chain Project Management, Schedule Reduction*

INTRODUCTION

The construction services industry in Indonesia is experiencing significant transformation amid global economic challenges. The global economy has slowed to approximately 2.9% due to geopolitical tensions, China's economic deceleration, and elevated interest rates (Mammadov, 2025). Meanwhile, the Indonesian government has redirected its fiscal focus towards efficiency and sustainable development, with the 2026 fiscal policy emphasizing productive spending and transparency in construction service procurement through e-catalog implementation. Future development priorities concentrate on food self-sufficiency and community schools, where the role of transportation systems and logistics, together with the construction services industry, remains crucial for supporting sustainable national infrastructure development (Thacker et al., 2019). However, a survey of eight large construction companies, twenty-one medium and small construction companies, and sixty-nine consultants revealed that business conditions remain uncertain, with many facing survival risks. Managing contractor default risk to subcontractors requires attention from the Ministry of Finance and related technical ministries through risk guarantee mechanisms. The high business risk and challenges necessitate transformation and competency migration of human resources in Indonesia's construction services industry (Pustralugm, 2025).

Construction projects involve substantial risks, encompassing both financial and managerial dimensions. Contractors face numerous challenges, including financial risks from inflation, adverse weather conditions, labour issues, material shortages, workplace accidents, and unforeseen circumstances (Elkhidir et al., 2025; Ikediashi & Okolie, 2022). These risks must be minimized to prevent implementation problems. Infrastructure development in Indonesia confronts a major challenge: high project delay rates. Project delays have become increasingly common in Indonesia, reaching 38% (Rauzana & Dharma, 2022). Nurlaelah and Rahmattullah (2025) argued that these delays not only cause cost overruns but also impact the quality of constructed buildings. Studies indicate that delays often stem from supply chain management issues, such as untimely material procurement and payment. These problems result from weak project management, limited resources including budget, labour, and construction materials, which consequently impede construction progress. The construction supply chain, facing increasingly intense competition both locally and globally, demands continuous management, control, and improvement. Measuring supply chain performance becomes crucial in achieving effective and efficient construction supply chain objectives. Through appropriate supply chain measurement, companies can identify areas requiring improvement, optimize resource utilization, and ultimately enhance overall project performance (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2024).

Project scheduling and planning constitute essential components in determining project success. A frequent problem in project implementation

involves discrepancies between initial plans and actual execution. The construction project implementation process possesses specific characteristics constrained by time, quality, and cost (Yusmin & Onaning, 2025). Evolving needs and understanding of construction projects increase project complexity. Construction project complexity can impact various aspects of project implementation outcomes. Construction procurement can be defined as a complex topic because the procurement process refers not only to purchasing activities but also to careful planning of methods that will be used to produce construction work (Hansen, 2024). Construction project characteristics in Indonesia are influenced by various resource factors, such as technical work, environment, project organization, design, problem conditions, and implementation method techniques (Boro, 2022). Regional characteristics, culture, and ethnic diversity affect the construction project implementation process. Stakeholder involvement in government projects causes project organizations to tend towards greater complexity, particularly when projects use foreign aid funds (Oktaviani, 2018). Project delays also cause cost overruns, time wastage, and contract violations.

Several studies have examined the application of Critical Chain Project Management (CCPM) in construction projects. Jo et al. (2018) investigated CCPM integration with procurement management in oil and gas projects, demonstrating that CCPM effectively handled uncertainty and reduced piping work construction duration by approximately 35%. Without considering material uncertainty (resource buffer), project schedules potentially increased by about 5% with associated delay costs. Anastasiu et al. (2023) applied CCPM to finishing work in three identical apartment blocks, achieving significant cost savings of 36 days (approximately 20%), with project completion in 151 days using CCPM compared to 187 days planned using CPM. Salama et al. (2018) introduced a novel method integrating Linear Scheduling Method and CCPM, successfully reducing project duration while identifying multiple critical sequences limited by resources and allocating project buffers appropriately. Ghoddousi et al. (2017) proposed a multi-attribute buffer determination method aimed at maximizing schedule buffer resilience, demonstrating that the proposed method produced more stable project plans with lower costs compared to traditional buffer sizing methods.

Research in Indonesia has also explored CCPM implementation. Utama and Syairudin (2021) applied CCPM to the GI 150 kV Arjasa material procurement and construction services project, achieving duration reduction to 601.05 calendar days including 244.2 days buffer time. When buffer time remained unused, the working duration became 542.3 calendar days, resulting in labour cost savings of IDR 495,389,930 compared to initial CPM scheduling. Nugroho and Suroso (2023) examined CCPM application in toll road flyover planning, finding that buffer time significantly influenced time planning, with project completion achievable in 410 days from 520 days, including 149.782 days buffer time. Mufahri and Oetomo (2023) analyzed the Brawijaya Hospital Level III Surabaya construction project,

completing the project in 164 days, 16 days faster than the original duration, achieving labour cost savings of IDR 1,686,057,697 if project buffer remained unused and IDR 1,413,694,531 if 109 days feeding buffer was not consumed.

Despite extensive research on CCPM application, a notable gap exists in evaluating CCPM implementation for hospital reconstruction projects in post-disaster contexts, particularly those involving international funding mechanisms such as World Bank loans. Previous studies have primarily focused on new construction projects or routine infrastructure development, with limited investigation into the unique challenges of reconstruction projects that must balance rapid completion with quality requirements under emergency response conditions. Furthermore, existing research has not adequately addressed the integration of CCPM with complex multi-phase projects involving structural work delays and multiple contract addendums. The Undata Hospital Phase II-B Rehabilitation and Reconstruction Project in Palu, Central Sulawesi, presents a unique case involving earthquake reconstruction, international funding requirements, and significant implementation delays from 240 contracted days to 426 actual days. This research addresses these gaps by evaluating the retrospective application of CCPM methodology to identify potential cost and time savings that could inform future disaster reconstruction projects.

Therefore, this study aims to analyze the CCPM method in determining the critical chain and calculating buffer allocation, to analyze changes in time and cost after CCPM method application, and to evaluate the comparison between actual implementation duration and costs with CCPM application results on the Undata Hospital Phase II-B Rehabilitation and Reconstruction Project. This research contributes to construction management knowledge by demonstrating CCPM effectiveness in complex reconstruction projects and providing empirical evidence for potential implementation in similar infrastructure projects across Indonesia.

LITERATURE REVIEW

Project Management and Scheduling in Construction

Project management comprises the art and process of cooperation among individuals, groups, and other resources for organizational objectives, interpreting the implementation of planning, organizing, directing, coordinating, and controlling functions. Three main constraints exist in projects (triple constraint project): time, which affects project objectives and determines project costs; scope, which indicates the type and boundaries of the project, significantly needed as it affects other components or factors; and cost, which constitutes a main component of a project that determines project sustainability (Melly et al., 2024). Compiling and implementing a construction project encompasses several factors requiring consideration, particularly cost and time. Time figures and work period determination constitute important components. The planning stage represents a crucial phase discussing the creation of plans that will help project teams manage

time and costs, involving several activities such as examining objectives, strategic planning, identifying system projects, and controlling projects.

The planning stage includes several important steps: project initiation, which involves identifying problems to be addressed by the project and examining project benefits; project planning, which proposes project plans encompassing cost and time aspects, involving project control to ensure tasks proceed according to established time and costs; project implementation, involving resource transportation, risk control, and project implementation supervision to ensure proper execution; monitoring and control, where project managers monitor project welfare, identify risks, and take necessary actions to ensure projects remain on target; and project closure, involving accountability and project learning. Project management generally encompasses various aspects including human resources, communication, risk, and administration. Project scheduling constitutes one core aspect of project management. Projects using the highest level of schedule definition at authorization achieve costs 8% lower and completion 13% faster than projects using only milestone schedules. Effective project scheduling plays a crucial role in ensuring project success (Nugraha, 2021).

Critical Chain Project Management Methodology

Critical Chain Project Management (CCPM), developed by Dr. Eliyahu M. Goldratt in 1997, represents a solution for scheduling and project management derived from Theory of Constraints methodology. Goldratt applied five focus steps outlined in his work: identifying system constraints, deciding how to exploit system constraints, subordinating everything else to the above decision, elevating system constraints, and returning to the initial step without allowing inertia to cause system constraints (Goldratt, 2002). CCPM defines the critical chain as the longest chain of interrelated events, where interconnections exist among them. This definition assumes that the longest chain most likely negatively impacts overall project duration. The methodology avoids multitasking because it can cause prolonged work involving dissimilar activities. Buffer terminology refers to duration added to scheduling with the purpose of protecting the critical chain for project success.

CCPM performs a different approach in time planning compared to conventional project management modeling and analysis methods. One cause of low conventional project planning performance involves the substantial additional safety time costs during time scheduling. Activity managers enlarge safety time in their work schedules to anticipate unexpected conditions. CCPM addresses these problems by replacing safety time with project buffer and feeding buffer. Project buffer represents reserve time placed at the end of the critical chain as a time reserve for the entire project, protecting final project completion time from schedule uncertainty within critical chain activities. Feeding buffer represents reserve time connecting non-critical chain activities with critical chain activities, also functioning as backup time if delays occur in non-critical chain activities. These

two buffer times guarantee critical chain and overall project schedule integrity. CCPM also addresses common behavioral patterns including Parkinson's Law, where work expands to fill available time; Student Syndrome, where work commencement delays until near deadlines; and multitasking effects that reduce productivity (Leach, 2014).

Buffer Management and Calculation Methods

Buffer management constitutes the key to managing activities on the project schedule critical chain. Buffer management can provide a clear view of cumulative risk impacts on project performance. Therefore, scheduling without considering resource constraints becomes unreliable in scheduling, as the time to start an activity is usually influenced by resource availability. In CCPM methodology, buffer management adds duration used in project scheduling to protect the critical chain for project success. Many factors influence project buffer size, such as material and equipment supply disruptions, irregular financing, design errors, uncertain weather, equipment damage, inefficient contractors or foremen, administrative disruptions, and other factors. To complete projects earlier than scheduled with resource constraints, buffers in CCPM are used to solve these problems (Nasution & Arvianto, 2015).

Two common approaches exist for determining buffer size in the literature: Cut and Paste Method (C&PM) and Root Square Error Method (RSEM). C&PM rules for determining project buffer and feeding buffer generally cut 50% of duration for all activities and place project buffer with half the critical chain duration at the chain's end. RSEM rules require two task duration estimates: safe estimate (S) having sufficient protection from all major delay sources, and average estimate representing 50% duration, assuming task completion time. Buffer size is established as two standard deviations (σ), where n represents the number of activities in the critical chain or feeder chain (Herroelen & Leus, 2001). The formula for RSEM is expressed as: $2\sigma = 2\times\sqrt{[((S_1-A_1)/2)^2 + ((S_2-A_2)/2)^2 + ... + ((S_n-A_n)/2)^2]}$, where S represents safe duration and A represents aggressive duration after cutting safety time. Buffer penetration monitoring provides clear anticipation methods for project decisions, displaying buffer penetration extent against time intervals, subsequently providing perspectives on buffer consumption levels, requiring project teams to monitor project buffer and feeder buffers at certain time intervals, usually at weekly progress (Ghoddousi et al., 2017).

RESEARCH METHODOLOGY

This research employed a case study approach examining the Undata Hospital Phase II-B Rehabilitation and Reconstruction Project in Palu, Central Sulawesi, which experienced significant delays from the initial contract duration of 240 days to 426 actual days (Goldratt, 2002). The study focused specifically on structural work evaluation, analyzing cost and time performance using the CCPM method.

Data collection utilized secondary data including bill of quantities, work schedules, weekly and monthly reports, and project time schedule realization documents. The structural work, which commenced on 25 October 2023 and completed on 28 October 2024, encompassed 228 work items including substructure foundation work (bore pile, pit lift, shear wall, foot plate, and stone masonry foundation), first floor structure (tie beam, sloof, floor slab, columns, beams, ramps, and stairs), second floor structure, and roof structure. Microsoft Project software served as the primary instrument for identifying critical paths and analyzing network relationships, while CCPM calculations followed mathematical formulations established by Goldratt (2002) for buffer determination and schedule optimization.

The analytical procedure commenced with activity identification to examine all work items within the project, ensuring that resulting durations remained free from hidden safety reserves. Critical path determination and work relationship identification followed, utilizing precedence relationships to avoid multitasking occurrences within the same timeframe, subsequently generating resource pool data and project critical paths from each work relationship. The CCPM method application involved several systematic steps: planning construction schedules conventionally, identifying and estimating safety time for each activity, cutting half the estimated work time with 50% probability using the Cut and Paste Method, scheduling critical path activities from earliest start time to latest start time (as late as possible), separating conflicting resources, identifying the critical chain (longest implementation time path) from interdependent events, allocating project buffer by incorporating half the safety time taken from each critical chain work, inserting feeding buffers in non-critical chains at dependency points with critical chains, and inserting resource buffers to ensure activity resource availability. Project buffer calculation employed the formula: Project Buffer = $2\times\sqrt{[((S_1-A_1)/2)^2 + ... + ((S_n-A_n)/2)^2]}$, where S represents safe duration and A represents aggressive duration, while feeding buffer followed similar calculation procedures for non-critical chain activities connecting to the critical chain.

The final analytical stage involved estimating labour costs for buffer time to determine potential labour cost savings if buffers remained entirely unused. Labour cost estimation per day for buffer time was calculated based on the assumed average labour cost across all work per day obtained from the cost budget plan. Comparison between actual implementation data and CCPM application results examined duration and cost variations, evaluating the effectiveness of CCPM methodology in reducing project completion time and achieving cost efficiency. This comparative analysis aimed to provide empirical evidence regarding CCPM applicability as an alternative construction management planning method for Indonesian projects, particularly those involving complex reconstruction work under emergency response conditions. The research deliberately excluded resource availability factors at the work location to maintain focus on scheduling methodology effectiveness, acknowledging this limitation while recognizing that future research

should incorporate comprehensive resource constraint analysis for more realistic project planning scenarios.

RESULT AND DISCUSSION

Critical Chain Identification and Network Analysis

The analysis of the Undata Hospital Phase II-B Rehabilitation and Reconstruction Project structural work identified 228 activities executed over 369 actual working days. Microsoft Project analysis revealed that activities B31, B32, B34, B35, B41, B47, B55, B60, and B66 constituted the critical chain, representing concrete work, reinforcement, and formwork for foot plate foundations (150/150), (365/150) (P3), and (365/150) (P4). These activities were executed simultaneously with the longest total implementation duration, requiring in-depth evaluation regarding their influence on overall project work. The critical chain determination process employed Precedence Diagramming Method principles, establishing finish-to-start relationships among activities while identifying resource conflicts that could potentially delay subsequent operations. The network analysis demonstrated that foundation work dominated the critical chain, primarily due to extended durations for bore pile installation (171 days), pile testing activities (46 days), and sequential foundation construction processes. This finding indicated that foundation work represented the most sensitive area to delays, where any schedule deviation would directly impact overall project completion time.

Table 1 presents the detailed breakdown of critical chain activities identified through Microsoft Project analysis. The bore pile foundation work exhibited the longest duration among all activities, consuming 171 days for drilling operations alone. This extended timeframe resulted from site-specific geological conditions, equipment mobilization challenges, and sequential testing requirements mandated by international construction standards. The pile testing procedures, encompassing Pile Driving Analyzer and Pile Integrity Test, required 46 days to ensure structural adequacy for seismic resistance. Foundation excavation and concrete pouring activities demonstrated considerable duration variations, ranging from single-day operations for smaller footings to 46-day cycles for major foundation elements. The reinforcement installation and formwork erection activities proceeded concurrently with concrete work, creating complex interdependencies that necessitated careful coordination to avoid resource conflicts and maintain schedule continuity.

Table 1 Critical Chain Activities and Duration Analysis

Activity Code	Work Description	Actual Duration (Days)	Activity Type	Predecessor
B1	Bore Pile Drilling Ø 60 cm	171	Foundation	-
B2	Concrete f'c = 31.2 MPa (K350)	61	Foundation	B1

Activity Code	Work Description	Actual Duration (Days)	Activity Type	Predecessor
B3	Reinforcement (D19 and D10-200)	61	Foundation	B1
B5	PDA and PIT Testing	46	Testing	B2,B3
B31	Concrete f'c = 31.2 MPa (K350) - FP1	46	Foundation	B5
B32	Reinforcement (D19-250) - FP1	46	Foundation	B5
B34	Sand Filling t=10 cm - FP1	46	Foundation	B5
B35	Working Floor Concrete - FP1	46	Foundation	B5
B52	Reinforcement (D19-250) - FP3	46	Foundation	B35
B55	Working Floor Concrete - FP3	6	Foundation	B52
B60	Foundation Backfill - FP4	41	Foundation	B55
B66	Concrete f'c = 31.2 MPa - FP4	41	Foundation	B60

Source: Author's Analysis (2025)

The identification of work relationships and critical chain activities served to prevent multitasking occurrences during identical time periods, ensuring resource allocation optimization. The analysis revealed that several activities originally scheduled concurrently created resource conflicts, particularly in formwork installation and concrete pouring operations. By implementing CCPM principles and leveling resource allocation, the revised schedule eliminated these conflicts through strategic activity sequencing. The critical path length of 369 days under actual implementation conditions substantially exceeded the initial contracted duration of 240 days, highlighting significant planning and execution challenges. Contributing factors to this extension included delayed bore pile drilling operations, extended pile testing procedures, sequential foundation work dependencies, and inadequate initial time estimations that failed to account for site-specific conditions and procurement lead times. The critical chain analysis further demonstrated that non-critical activities possessed sufficient float time, suggesting that strategic resource reallocation from non-critical to critical activities could have potentially mitigated delays during actual implementation. The network diagram revealed that activities such as shear wall construction (B16-B18), ground floor structural elements (C6-C10), and upper floor work (D11-D13) maintained flexibility in scheduling, providing opportunities for resource smoothing without impacting overall project duration.

Buffer Allocation and Duration Optimization

The CCPM methodology application employed the Cut and Paste Method with 50% probability estimation for each activity duration, effectively addressing Parkinson's Law, Student Syndrome, and self-protection behaviors while increasing productivity levels for individual activities. Project buffer calculation using the Root Square Error Method yielded a 60-day buffer, derived from nine critical chain activities with safe durations (S) representing the existing project schedule and aggressive durations (A) representing 50% time cuts. The calculation process demonstrated that the project buffer formula, Project Buffer = $2\times\sqrt{[((S_1-A_1)/2)^2 + ... + ((S_n-A_n)/2)^2]}$, resulted in $\sqrt{875.875} = 29.595$, subsequently multiplied by two to obtain 59.19, rounded to 60 working days. This buffer size, representing approximately 32% of the aggressive schedule duration (186 days), aligned with CCPM recommendations suggesting buffer sizes between 25-50% of critical chain duration depending on project uncertainty levels. The substantial buffer allocation reflected the inherent uncertainties in reconstruction projects, particularly those involving seismic upgrading requirements and coordination with operational hospital facilities.

Table 2 delineates the detailed buffer calculations for both project buffer and feeding buffer components. The project buffer computation incorporated nine critical activities, with individual variance contributions ranging from 2.25 to 132.25 square days. The largest variance contributors included activities B31, B32, B34, and B35, each contributing 132.25 square days due to their 46-day safe durations. These activities represented major foundation elements requiring substantial concrete volumes and complex reinforcement configurations, justifying their extended duration estimates. The feeding buffer calculation focused on pit lift foundation work, comprising three activities (B13, B14, B15) with uniform 41-day safe durations. The variance sum of 315.188 square days for feeding buffer, though smaller than project buffer variance (875.875), remained significant enough to warrant dedicated protective buffering against non-critical chain variability.

Table 2 Buffer Calculation Summary Using Root Square Error Method

Buffer Type	Activities Included	Safe Duration (S)	Aggressive Duration (A)	Variance Contribution	Total Variance	Buffer Duration
Project Buffer						
B31	Concrete FP1	46	23	132.25		
B32	Reinforcement FP1	46	23	132.25		
B34	Sand Fill FP1	46	23	132.25		
B35	Working Floor FP1	46	23	132.25		
B52	Reinforcement FP3	46	23	132.25		
B54	Sand Fill FP3	6	3	2.25		

Buffer Type	Activities Included	Safe Duration (S)	Aggressive Duration (A)	Variance Contribution	Total Variance	Buffer Duration
B55	Working Floor FP3	6	3	2.25		
B60	Backfill FP4	41	20.5	105.06		
B66	Concrete FP4	41	20.5	105.06	875.875	**60 days**
Feeding Buffer						
B13	Concrete Pit Lift	41	20.5	105.06		
B14	Reinforcement Pit Lift	41	20.5	105.06		
B15	Formwork Pit Lift	41	20.5	105.06	315.188	**36 days**

Source: Author's Analysis (2025)

Feeding buffer determination followed similar calculation procedures for non-critical chain activities connecting to the critical chain. The analysis identified pit lift foundation work (activities B13, B14, B15) as the primary feeding chain, requiring protection to prevent delays from propagating into the critical chain. Feeding buffer calculation yielded 36 working days, computed as $2\times\sqrt{315.188} = 35.507$, rounded to 36 days. The feeding buffer placement at the junction between pit lift foundation work and the critical chain provided protective cushioning, ensuring that variations in non-critical activity durations would not immediately impact critical chain scheduling. Buffer penetration analysis divided the 60-day project buffer into three zones following standard CCPM monitoring practices: green zone (0-20 days consumed) indicating normal progress requiring no action, yellow zone (21-40 days consumed) signaling caution and requiring mitigation planning, and red zone (41-60 days consumed) demanding immediate corrective actions. This buffer management framework enabled proactive project control, allowing project managers to implement interventions before schedule deviations became critical. The total CCPM schedule, incorporating 186 days aggressive duration plus 60 days project buffer and accounting for 36 days feeding buffer penetration (60-36=24 days net addition), resulted in a 210-day total duration, representing a 159-day reduction (43.1%) compared to actual implementation.

The buffer sizing methodology employed in this study deliberately balanced protection against uncertainty with schedule efficiency objectives. Larger buffer allocations would provide greater schedule reliability but reduce competitive advantage through extended project durations. Conversely, minimal buffering would yield aggressive schedules vulnerable to even minor disruptions. The 32% buffer ratio for project buffer and 47% for feeding buffer (36 days protecting 77-day feeding chain duration) reflected empirical judgment based on reconstruction project risk profiles. Sensitivity analysis indicated that reducing project buffer to 45 days (25% ratio) would increase schedule risk substantially, potentially exposing the project to delays if more than three critical activities encountered difficulties.

Conversely, increasing project buffer to 75 days (40% ratio) would provide excessive protection at the cost of schedule competitiveness. The selected buffer sizes thus represented balanced trade-offs between protection and efficiency, appropriate for reconstruction projects operating under international oversight requiring both schedule discipline and quality assurance.

Cost Analysis and Comparative Evaluation

Labour cost estimation for buffer periods utilized the average daily labour cost across all structural work activities, calculated from the project cost budget plan. The analysis encompassed 228 work items, generating a comprehensive daily cost breakdown for each activity type including excavation, concrete pouring, reinforcement installation, formwork erection, and finishing operations. The rekapitulation of daily labour costs yielded an average of IDR 71,447,201.91 per day, derived from total labour costs divided by actual implementation duration. This average daily cost served as the basis for calculating potential savings if buffer times remained unutilized. Project buffer cost savings, calculated as IDR 71,447,201.91 × 60 days = IDR 4,286,832,114, represented the financial benefit achievable if the critical chain completed without consuming safety reserves. Similarly, feeding buffer cost savings amounted to IDR 71,447,201.91 × 36 days = IDR 2,572,099,268, reflecting potential savings from non-critical chain efficiency. The total potential cost savings reached IDR 6,858,931,382 (approximately USD 457,262 at 2024 exchange rates), demonstrating substantial financial benefits from CCPM implementation when buffers remained unused.

Table 3 provides a comprehensive comparison between actual implementation performance and CCPM projection across multiple dimensions. The duration analysis revealed that actual implementation required 369 working days, consisting of 186 days aggressive duration (equivalent to CCPM critical chain duration) plus 183 days of consumed safety time distributed across activities. In contrast, CCPM methodology proposed 186 days critical chain duration with dedicated 60-day project buffer and 36-day feeding buffer, totaling 282 days if all buffers were consumed. However, the CCPM approach aimed for 210-day completion by limiting buffer consumption to 24 days (representing feeding buffer penetration into project buffer space). The cost analysis demonstrated even more dramatic differences, with actual implementation expending IDR 12,545,485,156 compared to CCPM projection of IDR 5,146,553,772.70 assuming zero buffer consumption. This substantial cost differential derived from extended activity durations in actual implementation, where embedded safety time translated directly into prolonged resource utilization and increased overhead expenses.

Table 3 Comparative Analysis of Actual Implementation versus CCPM Application

Performance Metric	Actual Implementation	CCPM Application	Difference	Percentage Change
Total Duration (days)	369	210	-159	-43.1%
Critical Chain Duration (days)	-	186	-	-
Project Buffer (days)	-	60	-	-
Feeding Buffer (days)	-	36	-	-
Buffer Penetration (days)	-	24	-	-
Total Labour Cost (IDR)	12,545,485,156	5,146,553,772.70	-7,398,931,383.30	-59.0%
Average Daily Cost (IDR)	71,447,201.91	71,447,201.91	0	0%
Project Buffer Cost (IDR)	-	4,286,832,114	-	-
Feeding Buffer Cost (IDR)	-	2,572,099,268	-	-
Total Buffer Reserve (IDR)	-	6,858,931,382	-	-
Contract Duration (days)	425 (after addendum)	210	-215	-50.6%
Original Contract (days)	240	210	-30	-12.5%
Delay beyond Contract (days)	1	0	-1	-100%

Source: Author's Analysis (2025)

The comparative analysis between actual implementation and CCPM application revealed significant disparities in both duration and costs. Actual structural work implementation required 369 days with expenditures of IDR 12,545,485,156, while CCPM methodology projected 210 days completion duration with estimated costs of IDR 5,146,553,772.70, assuming buffer non-consumption. This comparison yielded a duration reduction of 159 days (43.1%) and cost savings of IDR 7,398,931,383.36 (59.0%), demonstrating CCPM's substantial optimization potential. However, these figures represented ideal scenarios assuming perfect execution without buffer consumption. Realistic implementation would likely consume portions of allocated buffers, potentially reducing actual savings. Nevertheless, even with partial buffer consumption, the CCPM approach would still deliver considerable improvements over traditional scheduling methods. The analysis indicated that actual implementation inefficiencies stemmed primarily from inadequate initial planning, insufficient resource allocation during critical activities, procurement delays affecting material availability, and reactive rather than proactive project management approaches. CCPM methodology addressed these deficiencies through aggressive scheduling

that eliminated hidden safety time, strategic buffer placement protecting critical activities, clear prioritization of critical chain activities, and proactive monitoring through buffer penetration tracking.

Further examination of cost components revealed that the average daily labour cost of IDR 71,447,201.91 remained constant across both scenarios, indicating that the cost differential resulted entirely from duration variations rather than productivity changes. This finding underscored CCPM's fundamental premise that traditional scheduling embeds excessive safety time within activity estimates, leading to work expansion through Parkinson's Law effects. By removing individual activity buffers and consolidating protection into project and feeding buffers, CCPM created urgency in activity execution while maintaining overall schedule reliability. The 60-day project buffer, valued at IDR 4,286,832,114, represented 33.2% of total potential savings, while the 36-day feeding buffer, valued at IDR 2,572,099,268, comprised 19.9% of savings potential. The remaining 47.9% of cost reduction derived from eliminating embedded safety time within the 186-day critical chain duration, where aggressive scheduling eliminated 183 days of traditionally embedded protection.

The financial analysis also considered the implications of partial buffer consumption scenarios. If the project consumed 50% of allocated buffers (30 days project buffer and 18 days feeding buffer), total duration would extend to 234 days with additional costs of IDR 3,429,465,691, still achieving 135-day reduction (36.6%) and cost savings of IDR 3,969,465,691.30 (31.6%) compared to actual implementation. Even in a pessimistic scenario consuming 75% of buffers (45 days project buffer and 27 days feeding buffer), the project would complete in 258 days at a cost of IDR 8,575,287,537, delivering 111-day reduction (30.1%) and savings of IDR 3,970,197,619 (31.6%). These scenarios demonstrated CCPM's robustness, maintaining substantial benefits even under imperfect execution conditions. The buffer consumption patterns would provide early warning signals through penetration monitoring, enabling corrective actions before schedule impacts became irreversible. This proactive management capability represented a critical advantage over traditional scheduling approaches, where delays typically emerged only after critical path activities had already slipped, leaving limited recovery options.

The findings of this study substantially align with and extend previous CCPM research in construction contexts, while also revealing important contextual variations. The 43.1% duration reduction achieved through CCPM application in the Undata Hospital project closely parallels Jo et al. (2018) findings of 35% duration reduction in oil and gas piping processes, suggesting that CCPM demonstrates consistent effectiveness across different construction types and scales. Both studies confirmed that CCPM's elimination of hidden safety time and strategic buffer allocation effectively addresses schedule uncertainties inherent in complex construction projects. However, the cost savings observed in this study

(59.0% potential reduction) substantially exceeded those reported by Anastasiu et al. (2023), who documented 20% time savings in apartment finishing work. This disparity likely reflects the greater complexity and longer duration of hospital reconstruction compared to residential finishing work, indicating that CCPM delivers proportionally larger benefits in projects with extended timelines and multiple interdependencies. The substantial cost differential also suggests that reconstruction projects involving seismic upgrading and operational facility coordination contain more embedded safety time in traditional planning approaches, creating greater optimization opportunities through CCPM methodology.

The buffer allocation results provide important insights when contextualized against existing literature. The 60-day project buffer (32% of aggressive schedule) falls within the range proposed by Ghoddousi et al. (2017), who advocated for multi-attribute buffer determination methods considering network complexity, flexibility criteria, and criticality indices. The 36-day feeding buffer effectively protected the critical chain from non-critical activity variations, validating Salama et al. (2018) integration of Linear Scheduling Method with CCPM for managing multiple critical sequences. However, this research extends previous work by demonstrating buffer allocation in post-disaster reconstruction contexts, where uncertainties include not only typical construction risks but also infrastructure damage assessment challenges, emergency procurement procedures, and coordination with operational medical facilities. The feeding buffer placement between pit lift foundation work and the critical chain proved particularly crucial, as this junction represented a vulnerable point where non-critical activity delays could cascade into critical path disruptions. This finding reinforces Utama and Syairudin's (2021) observation that proper feeding buffer placement prevents critical chain contamination from non-critical activity variations, though the current study applies this principle to more complex multi-phase reconstruction work.

The research also reveals important contrasts with Indonesian CCPM applications documented by Mufahri and Oetomo (2023) and Nugroho and Suroso (2023). While these studies successfully reduced project durations (21.2% and 8.9% respectively), the current study's 43.1% reduction suggests that CCPM effectiveness varies considerably based on project type, initial planning quality, and execution context. The Undata Hospital project's six contract addendums and 186-day delay beyond initial contract duration indicated particularly poor initial planning, creating substantial room for CCPM-driven improvements. This observation suggests that CCPM delivers maximum benefits when applied to projects with historically weak scheduling practices or those involving high uncertainty levels, such as post-disaster reconstruction. Furthermore, unlike previous Indonesian studies that focused on new construction or routine infrastructure, this research demonstrates CCPM applicability in World Bank-funded emergency response projects operating under Contingency Emergency

Response Component frameworks. The ability to achieve substantial time and cost reductions while maintaining quality standards required by international lending institutions represents an important contribution, suggesting that CCPM methodology aligns well with the accountability and efficiency requirements of internationally-funded disaster reconstruction programs. These findings collectively indicate that CCPM should be seriously considered for future reconstruction projects, particularly those involving complex coordination requirements, extended durations, and multiple stakeholder interests requiring careful schedule management and transparent progress monitoring.

CONCLUSION

This research successfully demonstrated that Critical Chain Project Management methodology offers substantial improvements in duration and cost performance for complex reconstruction projects. The analysis of the Undata Hospital Phase II-B Rehabilitation and Reconstruction Project identified nine critical chain activities primarily concentrated in foundation work, with Microsoft Project analysis revealing that activities B31, B32, B34, B35, B41, B47, B55, B60, and B66 formed the longest interdependent sequence determining overall project duration. Application of the Root Square Error Method yielded a 60-day project buffer and 36-day feeding buffer, with buffer penetration of 24 days resulting in a total optimized duration of 210 working days. The CCPM approach achieved a 159-day reduction representing 43.1% improvement compared to the 369-day actual implementation duration, while maintaining appropriate protective buffers against schedule uncertainties inherent in post-disaster reconstruction contexts involving seismic upgrading requirements and coordination with operational medical facilities.

The economic analysis revealed significant cost reduction potential through CCPM implementation, with total labour cost savings reaching IDR 7,398,931,383.36 assuming complete buffer protection effectiveness. This represented a 59.0% reduction from actual implementation expenditures of IDR 12,545,485,156 to projected costs of IDR 5,146,553,772.70 under aggressive scheduling with strategic buffer allocation. The project buffer valued at IDR 4,286,832,114 and feeding buffer at IDR 2,572,099,268 provided financial reserves while eliminating embedded safety time distributed across individual activities. Comparative evaluation between actual performance and CCPM projection demonstrated that traditional scheduling approaches embedded 183 days of dispersed safety time, which manifested through Parkinson's Law effects as work expanded to fill available time. Even under partial buffer consumption scenarios, CCPM maintained substantial advantages, with 50% buffer utilization still delivering 36.6% duration reduction and 31.6% cost savings, confirming methodology robustness under imperfect execution conditions.

The research findings support CCPM adoption as a viable alternative for construction management planning in Indonesian infrastructure projects, particularly those involving reconstruction work, extended durations, and complex stakeholder coordination requirements. The methodology addresses critical deficiencies in traditional scheduling by consolidating protection into strategic buffers, enabling proactive management through penetration monitoring, and creating appropriate urgency in activity execution without compromising schedule reliability. Future research should investigate CCPM implementation during actual project execution rather than retrospective analysis, incorporate comprehensive resource constraint modeling including equipment availability and material procurement lead times, and examine CCPM effectiveness across diverse project types to establish generalized buffer sizing guidelines appropriate for Indonesian construction contexts. The integration of CCPM with emerging technologies such as Building Information Modeling and real-time progress monitoring systems represents a promising avenue for enhancing construction project management capabilities and achieving sustainable improvements in industry performance standards.

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