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Integrating Ecocriticality and Critical Path Method for Enhancing Time Efficiency and Reduce Environmental Impact

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A B S T R A C T

Time efficiency and environmental responsibility are increasingly recognized as essential dimensions of modern construction management. However, most scheduling studies using the Critical Path Method (CPM) primarily focus on duration optimization, whereas the ecological impacts associated with critical activities remain overlooked. This study aims to combine CPM with an ecocriticality-based assessment of time efficiency by considering the associated ecological burden. A case study was conducted on the construction of the Integrated Laboratory and Landscape Building at the Habibie Institute of Technology in Parepare, Indonesia. Project scheduling data, cost budget documents, and material volume records were analyzed to identify critical path activities and quantify their ecological burden. Ecocriticality Index (IE) was assessed based on four weighted environmental parameters, such as material consumption, solid waste generation, reuse potential, and embodied emissions. The results show that the integration of CPM with Ecocriticality provides a more comprehensive scheduling basis by simultaneously combining time efficiency and ecological burden. Its application resulted in an optimal duration of 1 week faster and identified floor and foundation elements with the highest environmental impact and located on the critical path. This integration also produced three priority schemes that can be used as a basis for selecting intervention strategies. These findings confirm that project acceleration decisions cannot be separated from ecological assessments. The integration of CPM and Ecocriticality provides an approach that can be applied to various projects to improve time efficiency while reducing environmental impacts and supporting sustainable construction.

1. Introduction

The construction of the Integrated Laboratory and Landscape Building at the Habibie Institute of Technology in Parepare City presents unique challenges due to its multi-level structural configuration and high material intensity, particularly in concrete-dominated

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structural works. Project monitoring records show that the highest implementation deviation occurred in the 29th week, reaching –9.995%, indicating a substantial schedule delay. This deviation reflects a critical imbalance between planned and actual progress. If not mitigated, it can extend the project completion time and escalate operational and financial risks. In addition, due to the large volume of structural elements and continuous material inflow, schedule delays intensify ecological burdens through prolonged resource consumption, increased waste accumulation, and higher embodied emissions [1].

To address the identified scheduling deviations and ecological pressures within the project, a combined analytical framework is needed to evaluate the time sensitivity of activities and their environmental burdens. The Critical Path Method (CPM) provides a systematic mechanism for identifying activity sequences that directly control project duration [2]. Through calculations of early–late start and finish times [3], [4], CPM highlights activities with zero float that must be executed without delay to prevent further schedule deviations [5], [6]. CPM is very effective for optimizing duration and prioritizing critical activities [7], [8]. However, this method only considers time and cost and does not inherently consider ecological impacts. To complement this limitation, the concept of ecocriticality is introduced as an operational adaptation of ecocriticism, a theoretical framework originating from the environmental humanities that critically examines human and nature relations [9]. Ecocriticality is redefined as a quantitative assessment of ecological load associated with construction activities, incorporating material consumption, waste generation, reuse potential, and embodied emissions [10], [11]. The results provide a quantitative picture of the contribution of each activity to the ecological impact of the project, which is the basis for sustainability evaluation in the context of time and resource efficiency [12]. Integrating CPM with ecocriticality allows critical path activities to be analyzed through the lens of schedule vulnerability and ecological burden. This integration is particularly relevant for projects with high material intensity, where delays not only extend completion time but also amplify waste accumulation and emissions [13]. This will directly contribute to the concept of sustainable construction [10], [14].

The application of the Critical Path Method (CPM) has been widely examined in construction scheduling, primarily for improving project duration and cost performance. Several studies demonstrate that CPM effectively optimizes timelines across various project contexts, such as residential building projects where CPM reduced construction duration by more than 9% while lowering cost overruns [15]. Similar findings were reported in road construction scheduling, where CPM and productivity simulation enabled better structuring of

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work sequences and resource use [16]. These studies highlight CPM's strength in time–cost optimization but do not incorporate environmental impact considerations. With the rise of sustainability awareness, research has increasingly explored scheduling models that integrate environmental dimensions. Early work introduced the time–cost–environment (TCE) trade-off framework to evaluate environmental impact alongside duration and cost objectives [17]. Subsequent studies expanded this approach by incorporating multi-objective optimization, addressing trade-offs among time, cost, quality, and carbon emissions [18], or applying robust optimization to manage uncertainty within TCE scheduling problems [19]. Other studies employed multi-criteria decision-making to incorporate environmental factors into time–cost trade-off alternatives [20]. Previous research shows a growing trend to embed environmental concerns within scheduling models, although environmental impacts are treated as separate optimization objectives rather than components of activity-level criticality. Overall, prior research shows substantial progress in linking scheduling and environmental assessment through trade-off modeling and emission-based evaluation. However, existing studies do not incorporate theoretical foundations of ecological critique such as ecocriticism into quantitative engineering frameworks. Integrating ecocriticality into CPM allows critical paths to be evaluated as determinants of time-dependent risk and environmental burdens.

This study aims to combine the Critical Path Method with an ecocriticality-based assessment for time efficiency by considering the associated ecological burden. This analysis utilizes project scheduling data, detailed cost budgets, and material volume records from the construction of the Integrated Laboratory and Landscape Building at the Habibie Institute of Technology in Parepare City. CPM is applied to identify activities that govern the project duration, while the ecocriticality assessment quantifies the ecological burden. The integration of these two analytical dimensions is expected to produce a scheduling framework that can be applied to various projects to improve time efficiency while reducing environmental impacts and supporting sustainable construction.

2. Research Method

This study focuses on developing an Eco-CPM framework by combining Critical Path Method calculations with ecocriticality-based evaluations derived from material consumption, waste generation, reuse potential, and embodied emissions. Using a case study of the Integrated Laboratory and Landscape Building project at the Habibie Institute of Technology in Parepare City, this study quantitatively analyzes project data to identify activities that are simultaneously critical in terms of schedule sensitivity and ecological burden, thus supporting sustainability-

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oriented project management.

2.1 Data

Data for this study were obtained from project scheduling documents, cost budget reports, and detailed material volume records associated with the construction of the Integrated Laboratory and Landscape Building [12], [13]. The scheduling data include activity sequences, durations, and dependency relationships required for CPM calculations, while the budget documents provide information on material quantities, structural components, and resource allocation. Additional environmental parameters such as standard waste percentages, reuse potential, and embodied emission factors were derived from relevant literature to support the ecocriticality assessment.

2.2 CPM Analysis

The analysis focused on identifying the earliest and latest possible times for each activity to start and finish within the project network. The analysis began with identifying all construction activities and mapping their precedence relationships to form a complete project network. Forward pass calculations were then performed to determine Early Start (ES) and Early Finish (EF) times, followed by backward pass calculations to derive Late Start (LS) and Late Finish (LF) times [21]. Total Float (TF) and Free Float (FF) values were computed to assess schedule flexibility and identify activities with zero float, which form the project's critical path and therefore directly govern the total project duration [22].

2.3 Ecocriticality Assessment

The ecocriticality assessment was conducted to quantify the ecological load associated with each construction activity by adapting the conceptual foundation of ecocriticism into an operational engineering framework [23]. The assessment began by identifying the activities on the project's critical line and calculating the corresponding material volumes involved in their execution, particularly for material-intensive components such as concrete, brick, and steel. Standard waste percentages from literature ; 5–8% for concrete, 3–5% for brickwork, and approximately 2% for steel were applied to estimate potential solid waste generated from leftovers, cutting losses, and dismantled materials. Standard waste percentages are adopted referencing empirical studies reported that concrete and masonry contribute over 60% of total construction waste, supporting the 5–8% concrete waste assumption; additional evidence highlights the substantial share of concrete/masonry in overall waste generation globally, justifying the use of these benchmark values in this study [24]. Each activity was then evaluated using a weighted Likert scale (1–5) that considers material consumption, waste generation,

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reuse potential, and embodied emissions [25]. Activities with higher index values were interpreted as having a greater ecological burden. The weighting coefficients in the Ecocriticality Index (IE) formulation were determined based on the relative contribution of each parameter toward ecological burden in construction. Previous studies indicate that material consumption and solid waste generation contribute the largest share of environmental impact in building projects, particularly for concrete-intensive works [26]. Therefore, Smaterial was assigned the highest weight of 0.4, reflecting the primary role of raw material extraction and manufacturing in environmental degradation. Solid waste (Swaste) was weighted at 0.3 because improper waste handling is the second-highest contributor to the environmental footprint in typical construction settings. Meanwhile, reuse potential (Sreuse) was assigned a lower weight of 0.2 due to the relatively limited reuse capability of major structural elements such as cast-in-place concrete [26]. Emission-related impact (Semission) was given a weight of 0.1, representing its difficulty to measure precisely under limited field data availability and the fact that its contribution may be indirect when compared to material and waste impacts in reinforced concrete structures. These parameters were incorporated into an ecocriticality index calculated using Equation 1.

$$\mathrm{IE} = (0.4 \times \mathrm{Smaterial}) + (0.3 \times \mathrm{Swaste}) + (0.2 \times \mathrm{Sreuse}) + (0.1 \times \mathrm{Semission}) \quad (1)$$

3. Results and Discussions

3.1 Critical Path Analysis

Table 1. Critical Path Analysis Results

No	Symbol	Activity	Description	No	Symbol	Activity	Description
1	A	Prep Work	Critical	12	L	Semi Basement *and* Basement *Architecture Work*	Non-Critical
2	B	Occupational Safety K3 Jobs	Non-Critical	13	M	1st Floor Architectural Work	Critical
3	C	Foundation Structure Work and Basement Semi Flooring	Critical	14	N	2nd Floor Architectural Work	Critical
4	D	Basement Floor Structure Work	Critical	15	O	3rd Floor Architectural Work	Critical
5	E	1st Floor Structure Work	Critical	16	P	4th and 5th Floor Architectural Works	Critical
6	F	2nd Floor Structure Work	Non-Critical	17	Q	Top Floor and Facade Architecture Work	Critical
7	G	3rd Floor Structure Work	Non-Critical	18	R	Electrical Work	Critical
8	H	4th Floor Structure Work	Non-Critical	19	S	Mechanical Work	Critical
9	I	5th Floor Structure Work	Non-Critical	20	T	Mechanical Work	Critical
10	J	Top Floor Structure Work	Non-Critical	21	U	Landscaping Work	Critical
11	K	Stair Structure Work	Critical	22	V	Cleaning Work	Critical

Source: Author Research Results (2025).

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The results of the data processing (**Table 1**) showed that the calculation of project scheduling using the CPM results identifies 15 critical activities, namely A, C, D, E, K, M, N, O, P, Q, R, S, T, U, and V, which directly determine the total project duration. Meanwhile, seven non-critical activities have float values that allow schedule flexibility without affecting the project completion time. Meanwhile, according to the implementing agency's plan, the project completion time was set at 37 weeks using the S-curve method. CPM can produce a more efficient estimate of project completion duration, which is one week faster (36 weeks). This reinforces CPM's excellence in identifying critical pathways, allowing for more structured and timely management of activity priorities. Thus, CPM can be used as a strategic approach in optimizing project scheduling, especially in the construction project of the Integrated Laboratory Building and Landscaping of the Habibie Institute of Technology. This efficiency reflects that the implementation of CPM not only supports the effectiveness of time control but also provides a quantitative basis for project scheduling decision-making that is more rational and adaptive to the needs of the acceleration of construction projects.

3.2 Ecocriticality

From the results of the study of the detailed document on the cost of the Habibie Parepare IT Integrated Laboratory project, the following actual concrete volume data was obtained as shown in **Table 2**.

Table 2. Structural Element Volume Data and Ecocriticality Assessment

Structural Elements	Concrete volume (m³)	Waste (m³)	IE
Foundation (semi basement + pile cap + footplate)	127,39	10,19	3,64
Sloof	37,55	3,00	2,62
Column	21,43	1,71	2,24
Floor Plates	167,17	13,37	4,30
Ladder	14,50	1,16	2,07
Total Volume	368,04	29,43	

Source: Author Research Results (2025).

The floor slabs are the most ecologically critical element with an IE of 4.30. The foundation occupies the second position with an IE of 3.64, due to its high volume and waste. Columns and sloofs have an intermediate impact of around 2.2 – 2.6. The stairs are relatively small, resulting in a low IE of 2.07. The high ecological index of the floor slabs is primarily influenced by the large volume of concrete used and the limited potential for material reuse. Meanwhile, the foundation has a high score mainly due to waste generation during pile cap casting and excavation works. Columns and sloofs show moderate ecological sensitivity because their construction involves repetitive but smaller-volume components. The stairs have

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the lowest impact due to their limited material consumption and smaller affected area. Based on ecocriticality analysis, the highest IE values are for floor slabs and foundations. These two elements are also part of the critical path of CPM, so they have the highest priority in mitigating ecocriticality.

3.3 Eco-CPM Integration

The integration of CPM results with the Ecocriticality Index (IE) highlights how time-critical activities can simultaneously impose substantial environmental burdens. The analysis shows that floor slabs and foundations not only govern project duration but also generate the highest ecological load, indicating they must receive top priority for schedule control and environmental mitigation. Conversely, stairs exhibit high time-criticality but lower IE, suggesting a priority focus on work pacing rather than environmental measures. This integrated assessment forms a more comprehensive prioritization model that supports decision-making based on both timely delivery and ecological responsibility, ensuring that acceleration strategies do not lead to increased waste, excess material use, or emissions.

The integration of the CPM and Ecocriticality Index results yields three priority categories used to determine the need for intervention in each activity group. Priority 1 includes activities that are on the critical path and have a high IE value. These activities require immediate dual action: accelerated implementation to maintain schedule stability and the implementation of environmental mitigation strategies such as waste reduction and material emission control. Priority 2 consists of activities that are also on the critical path but have a medium or low IE value, so the management focus is more directed at time control without the need for intensive ecological mitigation. Meanwhile, Priority 3 includes non-critical activities but has a high IE value; these activities do not affect the total project duration, but still require environmental mitigation efforts to avoid increasing the project's overall ecological footprint.

Table 3. Eco-CPM Priority Schemes Based on Real Ecocriticality Index (IE) Values

Priority Scheme	Description of Scheme	Included Activities	Associated Structural Elements	IE Values of Structural Elements	Resulting Total IE	Adjusted Project Duration (Weeks)
Priority 1 (High Time-Critical + High Eco-Critical)	Critical-path activities require simultaneous schedule control and ecological mitigation.	A, C, D, E, M	Floor Slab and Foundation	4.303.64	7.94	36
Priority 2 (High Time-Critical + Moderate/Low Eco-Critical)	Critical-path activities require time-focused acceleration with moderate ecological concerns.	O, P, Q, R	Column and Sloof	2.602.27	4.87	36

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Priority Scheme	Description of Scheme	Included Activities	Associated Structural Elements	IE Values of Structural Elements	Resulting Total IE	Adjusted Project Duration (Weeks)
Priority 3 (Non-Critical + High Eco-Critical Impact Zone)	Non-critical activities are prioritized for environmental mitigation without affecting the schedule.	X, Y, Z	Stairs	2.07	2.07	37 *(no acceleration needed)*

Source: Author Research Results (2025).

The Eco-CPM prioritization results presented in **Table 3** show that Priority 1 consists of critical-path activities associated with floor slabs and foundations, generating the highest combined ecological burden. These activities require integrated time–environment interventions to avoid delays and material-related impacts. Priority 2 includes other critical-path works such as columns and sloof, which exhibit moderate IE values, indicating that schedule control remains the main concern while environmental risks are comparatively lower. Priority 3 comprises non-critical activities with notable ecological implications, such as stair construction, where environmental mitigation can be implemented without affecting the project timeline. This three-tier structure clarifies how Eco-CPM supports balanced decision-making by aligning schedule priorities with environmental performance.

The high EI identified for floor slabs and foundations indicates that these structural activities require priority mitigation to reduce environmental burdens while maintaining schedule efficiency. Practical strategies that can be implemented include improving formwork efficiency, adopting prefabricated structural components, enhancing batching and slump control to reduce concrete excess, and optimizing reinforcement cutting to minimize steel waste. These approaches have demonstrated effectiveness in lowering construction waste and embodied carbon in similar projects [28]. This study evaluates an Eco-CPM framework using a single construction project as a case study. While the analytical approach and assessment framework are transferable and may be applied to other building types, variations in material composition, construction methods, and environmental management practices may influence the resulting IE.

The findings of this study align with sustainability theory, which emphasizes that construction activities with high material intensity and waste potential generally contribute the greatest ecological burden [27], [28]. The Eco-CPM results also reinforce previous evidence indicating that structural elements, particularly concrete slabs and foundations, are major sources of waste and embodied environmental impact in building projects [29]. Compared with earlier time–cost–environment (TCE) studies that treat environmental impact as a post-planning

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trade-off, this research advances the field by integrating ecological scoring directly into CPM logic, making environmental impact a determining dimension of activity criticality. The key finding that the slab and foundation activities have the highest Ecocriticality Index while also lying on the critical path demonstrates that time efficiency and ecological performance must be managed concurrently. This provides a clear practical implication: acceleration and control strategies for these activities should prioritize both schedule stability and ecological mitigation, strengthening the relevance of the Eco-CPM framework for sustainable construction planning.

4. Conclusion

This study demonstrates that the integration of CPM with Ecocriticality provides a more comprehensive scheduling basis by simultaneously combining time efficiency and ecological burden. Its application to the Integrated Laboratory and Landscape Building project resulted in an optimized duration of 36 weeks and identified structural elements with the highest environmental impact, namely floors and foundations, which are also on the critical path. This integration also produced three priority schemes that can be used as a basis for selecting intervention strategies such as a scheme that focuses on critical activities with high EI for acceleration and simultaneous reduction of environmental impact, a scheme that focuses on time control for critical activities with medium to low EI, and an environmental mitigation scheme for non-critical activities with high EI values without affecting the total project duration. These findings confirm that scheduling decisions cannot be separated from ecological assessments in material-intensive construction activities and provide an approach that can be applied to various projects to improve time efficiency while reducing environmental impact and supporting sustainable construction.

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