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The Application of Preventive Maintenance to Improve Heavy Equipment Performance in Construction Projects

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Abstract

Heavy equipment is one of the most critical resources in construction projects, directly influencing project completion in terms of schedule, cost, quality, and operational efficiency. Intensive equipment utilization increases the risk of mechanical failures, making systematic maintenance essential to ensure continuous operation and minimize unexpected disruptions. This study aims to evaluate the implementation of Preventive Maintenance (PM) in improving the operational performance of heavy equipment used in construction projects. An empirical quantitative case-study approach was employed using operational records, maintenance schedules, equipment operating hours, downtime data, and maintenance documentation collected from the Nakau–Taba Mulan Road Landslide Reconstruction Project, Central Bengkulu Regency, Indonesia. Equipment performance was evaluated using key maintenance indicators, including Availability, Reliability, Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR), Productivity, and Overall Equipment Effectiveness (OEE). The findings indicate that systematic preventive maintenance significantly reduced equipment downtime while increasing operational availability, reliability, and productivity. The heavy equipment achieved an Availability of 98.90%, a Reliability of 96.00%, and an Overall Equipment Effectiveness (OEE) of 92.03%, indicating world-class operational performance. These results demonstrate that preventive maintenance is an effective maintenance strategy for enhancing equipment reliability, improving operational efficiency, reducing emergency repair costs, and supporting the successful execution of construction projects.

Keywords: *Availability, Downtime, Heavy Equipment, Preventive Maintenance, Productivity.*

INTRODUCTION

The construction industry has experienced rapid transformation over the past decade as governments and private sectors worldwide continue to intensify investments in transportation networks, industrial facilities, energy infrastructure, and urban development projects that demand increasingly sophisticated construction technologies and management strategies. Heavy equipment has consequently become an indispensable asset in modern construction because its operational capability directly determines project productivity, work quality, schedule adherence, and overall resource utilization throughout the project life cycle (Peurifoy et al., 2018). Recent technological developments have introduced advanced hydraulic systems, intelligent monitoring devices, telematics, and digital control technologies that substantially improve the operational efficiency and precision of heavy-duty construction machinery (Khan et al., 2022). Despite these technological advancements, the operational performance of heavy equipment remains highly dependent on systematic maintenance practices rather than technological sophistication alone. Construction projects frequently operate under demanding environmental conditions characterized by continuous workloads, fluctuating operating hours, abrasive materials, and harsh weather, all of which accelerate component degradation and increase the probability of unexpected equipment failures. These operational challenges have encouraged construction organizations to shift their attention from reactive maintenance practices toward preventive maintenance strategies capable of minimizing equipment deterioration before critical failures occur (Akbar et al., 2024). As maintenance management increasingly becomes an integral component of project performance optimization, understanding how preventive maintenance contributes to improving heavy equipment performance represents an important issue within intelligent engineering and construction management research.

Previous studies consistently demonstrate that preventive maintenance contributes significantly to improving equipment reliability, operational availability, and long-term productivity across various industrial sectors, although the magnitude of these improvements varies depending on maintenance planning and implementation quality. Research conducted in Indonesian heavy equipment operations reported that scheduled preventive maintenance effectively reduced unexpected failures while increasing equipment availability during intensive operational activities (Saputra et al., 2023). Maintenance management has also evolved beyond conventional scheduling by integrating Total Productive Maintenance principles with digital maintenance information systems that enable better maintenance documentation, operator participation, and decision support for equipment management (Aulia & Putri, 2025). Other investigations emphasize that maintenance effectiveness is strongly associated with organizational performance because reduced downtime improves equipment utilization while simultaneously lowering operational expenditures and project interruption risks (Palomino-Valles et al., 2020). These findings collectively indicate that preventive maintenance should no longer be viewed merely as a routine technical activity but rather as a strategic management instrument that supports sustainable operational performance. Current developments in intelligent engineering further encourage the integration of maintenance planning with performance indicators, operational monitoring, and managerial decision-making to achieve higher equipment efficiency throughout construction projects. Existing evidence therefore establishes a strong theoretical foundation supporting preventive maintenance as a critical determinant of heavy equipment operational excellence.

Although previous investigations have confirmed numerous benefits of preventive maintenance, the existing body of knowledge remains fragmented because most studies examine isolated maintenance indicators without comprehensively evaluating their combined influence on equipment productivity, availability, reliability, and downtime within construction project environments. Several studies concentrate primarily on maintenance scheduling optimization or reliability-centered maintenance while paying relatively limited attention to how preventive maintenance simultaneously affects multiple operational performance indicators that determine project success (Manikandan et al., 2018). More recent studies have begun incorporating condition-based maintenance and operational performance assessment; however, these investigations generally emphasize mining industries or highly specialized operational contexts whose maintenance characteristics differ considerably from conventional construction projects (Prabowo et al., 2026). The increasing adoption of key performance indicators for heavy equipment management also reveals that operational improvements cannot be interpreted solely through financial outcomes because maintenance quality influences broader dimensions of asset performance and project execution effectiveness (Rosdianto et al., 2026). Such inconsistencies indicate that the practical relationship between preventive maintenance implementation and comprehensive heavy equipment performance remains insufficiently explained within construction-specific operational settings. Existing literature has not yet provided an integrated analytical framework capable of simultaneously evaluating preventive maintenance effectiveness through productivity enhancement, reliability improvement, availability optimization, and downtime reduction using operational maintenance records. This unresolved gap creates opportunities for further empirical investigation to strengthen both theoretical understanding and evidence-based maintenance management practices in contemporary construction projects.

The unresolved issues surrounding preventive maintenance have become increasingly important because construction projects are expected to achieve higher productivity while simultaneously maintaining cost efficiency, operational safety, and strict project schedules under increasingly competitive market conditions. Equipment failures that occur during critical construction activities not only increase maintenance expenditures but also generate cascading effects on resource allocation, labor productivity, material delivery, and overall project performance, making maintenance management a strategic rather than merely operational concern (Simatupang & Sridharan, 2016). Recent industrial evidence further indicates that reducing unplanned downtime through optimized maintenance planning and appropriate allocation of maintenance personnel can substantially improve equipment utilization while maximizing project profitability (Ami & Siallagan, 2026). Studies focusing on preventive maintenance strategies have likewise demonstrated that systematic maintenance scheduling extends equipment service life and minimizes long-term operational costs, particularly for heavy equipment operating under intensive working conditions (Suprapto, 2025). Despite these practical benefits, many construction organizations continue to implement preventive maintenance inconsistently because maintenance decisions are frequently driven by operational urgency instead of objective performance evaluation. This situation creates a significant disconnect between theoretical maintenance frameworks and their practical implementation, particularly in construction projects where equipment availability directly influences project completion time and contractual performance. A more comprehensive empirical assessment is therefore required to clarify how preventive maintenance contributes to measurable improvements in heavy equipment performance and to provide evidence capable of supporting more effective maintenance decision-making.

This study is positioned within the growing body of intelligent engineering and construction management research that seeks to optimize heavy equipment performance through systematic maintenance strategies supported by operational performance indicators. Unlike previous studies that primarily emphasize maintenance scheduling, isolated reliability analysis, or individual maintenance approaches, this research evaluates preventive maintenance through the integrated assessment of productivity, equipment availability, reliability, and downtime as interconnected dimensions of heavy equipment performance. Such an integrated perspective is expected to provide a more comprehensive understanding of how preventive maintenance influences operational effectiveness across the entire equipment utilization process rather than within a single performance indicator. The study also emphasizes the practical use of operational and maintenance records to evaluate maintenance effectiveness under actual construction project conditions, allowing maintenance performance to be interpreted within realistic industrial environments rather than controlled experimental settings. By integrating multiple operational indicators into a unified analytical framework, the research seeks to strengthen the empirical relationship between preventive maintenance implementation and overall heavy equipment performance while enriching current maintenance management literature. The findings are also expected to provide practical insights for construction companies in developing maintenance policies that improve equipment reliability without compromising operational efficiency. This research therefore occupies a complementary position within existing maintenance studies by bridging engineering maintenance principles with construction project performance evaluation.

The objective of this research is to analyze the implementation of preventive maintenance in construction heavy equipment and evaluate its influence on equipment productivity, availability, reliability, and downtime as key indicators of operational performance. The study also aims to examine the effectiveness of preventive maintenance in supporting more efficient equipment utilization throughout construction project execution by employing an integrated evaluation of operational and maintenance records. Through this approach, the research seeks to develop a comprehensive understanding of the relationship between systematic maintenance practices and heavy equipment performance within real construction environments. The proposed analytical framework is expected to contribute to the advancement of maintenance management theory by demonstrating the interdependence among major equipment performance indicators rather than treating them as isolated variables. From a methodological perspective, the study offers a holistic performance evaluation model that combines maintenance implementation with measurable operational indicators to support evidence-based maintenance decision-making. The findings are anticipated to provide practical recommendations for construction companies in designing maintenance strategies capable of improving equipment performance, reducing operational disruptions, and enhancing project efficiency. Ultimately, this research is expected to enrich the development of intelligent maintenance management practices that support sustainable and reliable construction project operations.

RESEARCH METHODS

This study employed an empirical quantitative case-study design to evaluate the effectiveness of Preventive Maintenance (PM) in improving the operational performance of heavy equipment used in construction projects. The research was conducted at the Nakau–Taba Mulan Road Landslide Reconstruction Project, Central Bengkulu Regency, Indonesia, from January to June 2026. The study focused on six categories of heavy equipment, namely excavators, bulldozers, wheel loaders, dump trucks, motor graders, and vibratory rollers operating during project implementation. The preventive maintenance activities evaluated included engine oil replacement, filter replacement, greasing, hydraulic system inspection, engine inspection, cooling system inspection, electrical system inspection, and undercarriage inspection according to scheduled maintenance intervals (Mobley, 2002). Primary data were obtained through field observations, structured interviews with site managers, supervisors, mechanics, and equipment operators, while secondary data were collected from maintenance logbooks, operating-hour records, equipment service histories, preventive maintenance schedules, manufacturer manuals, and maintenance cost reports (Wireman, 2005). The research procedure consisted of problem identification, literature review, field observation, data collection, maintenance record verification, calculation of equipment performance indicators, and interpretation of maintenance effectiveness. The overall maintenance evaluation framework followed systematic maintenance management procedures widely adopted for heavy construction equipment to ensure consistency and reproducibility of the analytical process (Duffuaa et al., 2000).

The effectiveness of Preventive Maintenance was evaluated using quantitative performance indicators consisting of Availability, Reliability, Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR), Productivity, Downtime, and Overall Equipment Effectiveness (OEE). Availability was calculated using Equation (1):

$$Availability = \frac{Operating\ Time}{Operating\ Time + Downtime} \times 100\%$$

where *Operating Time* represents the actual operating hours and *Downtime* represents the total non-operational hours due to equipment failure or maintenance.
Reliability was determined using Equation (2):

$$Reliability = \frac{MTBF}{MTBF + MTTR} \times 100\%$$

where MTBF is the Mean Time Between Failure and MTTR is the Mean Time To Repair.
MTBF was calculated using Equation (3):

$$MTBF = \frac{Operating\ Time}{Number\ of\ Failures}$$

where *Number of Failures* denotes the total recorded equipment failures during the observation period.
MTTR was calculated using Equation (4):

$$MTTR = \frac{Total\ Repair\ Time}{Number\ of\ Failures}$$

where *Total Repair Time* represents the cumulative repair duration required to restore equipment functionality.
Equipment productivity was estimated using Equation (5):

$$Q = \frac{q \times 60 \times E}{CT}$$

where $Q$is equipment productivity (m^3/h), $q$is bucket capacity (m^3), $E$is work efficiency, and $CT$is cycle time (minutes).
Overall Equipment Effectiveness (OEE) was calculated using Equation (6):

$$OEE = Availability \times Performance \times Quality$$

The calculated values before and after the implementation of Preventive Maintenance were comparatively analyzed using descriptive quantitative analysis to determine improvements in equipment productivity, availability, reliability, operational efficiency, and reductions in downtime. Data validity was ensured through triangulation by comparing field observations, maintenance documentation, interview results, and equipment operational records, while the interpretation of maintenance performance followed established equipment maintenance management principles and industrial performance evaluation standards (Nakajima, 1988). The use of standardized operational records, identical calculation procedures, and transparent analytical steps enables the proposed methodology to be reproduced in similar construction projects and provides a reliable basis for evaluating the effectiveness of preventive maintenance strategies in improving heavy equipment performance (Corder, 1992).

Research Hypotheses

H_0 (Null Hypothesis):

The implementation of Preventive Maintenance has no significant effect on the performance of heavy equipment in construction projects, as reflected by equipment productivity, availability, reliability, and downtime.

H_1 (Alternative Hypothesis):

The implementation of Preventive Maintenance has a significant positive effect on the performance of heavy equipment in construction projects by increasing equipment productivity, availability, and reliability while reducing downtime.

RESULTS AND DISCUSSION

Heavy Equipment Characteristics and Preventive Maintenance Implementation

The empirical investigation was conducted at the Nakau–Taba Mulan Road Landslide Reconstruction Project, Central Bengkulu Regency, where heavy equipment served as the primary production resources for earthmoving, grading, hauling, and compaction activities throughout the construction period. The project required continuous equipment operation under varying terrain conditions, making maintenance management an essential factor influencing operational continuity and project productivity. Field observations indicated that each equipment unit was subjected to routine inspections and scheduled maintenance based on accumulated operating hours and manufacturer recommendations before major construction activities commenced. The maintenance strategy adopted by the contractor emphasized preventive actions rather than reactive repairs to reduce the likelihood of unexpected equipment failures during critical construction operations. Such an approach is consistent with modern construction equipment management, which considers maintenance planning an integral component of operational efficiency rather than merely a technical support activity (Peurifoy et al., 2018). The implementation framework also reflected systematic maintenance planning in which inspection, servicing, and maintenance documentation were integrated into daily project management to improve equipment utilization and operational reliability.

The heavy equipment fleet observed during the study consisted of six categories of machines with different operational functions and capacities, allowing the maintenance strategy to be evaluated under diverse working conditions. Excavators were primarily employed for excavation and slope stabilization, bulldozers for land clearing and material pushing, wheel loaders for aggregate handling, dump trucks for material transportation, motor graders for road surface shaping, and vibratory rollers for soil compaction. The diversity of equipment required different maintenance intervals because each machine experienced distinct loading conditions, operating cycles, and component wear characteristics. Maintenance planning was therefore adjusted according to equipment specifications while maintaining standardized preventive maintenance procedures across the project. The distribution and technical specifications of the heavy equipment are summarized in Table 1, which illustrates the operational resources involved throughout the observation period. The composition of the equipment fleet demonstrates that maintenance management must accommodate heterogeneous machine characteristics while ensuring consistent operational performance across all equipment categories (Edwards et al., 1998).

Table 1. Heavy Equipment Used in the Construction Project

Equipment	Quantity	Capacity	Manufacturing Year
Excavator	2 Units	0.9 m³	2022
Bulldozer	1 Unit	D85	2021

Wheel Loader	1 Unit	2.5 m^3	2022
Dump Truck	5 Units	20 tons	2023
Motor Grader	1 Unit	140 HP	2022
Vibratory Roller	1 Unit	10 tons	2021

As presented in Table 1, most equipment consisted of relatively new units manufactured between 2021 and 2023, indicating that the project operated with machines possessing relatively high remaining service life. Nevertheless, the availability of modern equipment alone does not guarantee sustained operational performance because intensive construction activities accelerate mechanical wear, hydraulic deterioration, and lubrication degradation when maintenance activities are not consistently implemented. Field observations revealed that equipment operating under continuous loading conditions experienced higher maintenance requirements despite their relatively recent manufacturing years. These findings reinforce the principle that equipment age should not be considered the sole determinant of maintenance scheduling because operational intensity often becomes a more influential factor in predicting equipment deterioration. Modern maintenance management consequently recommends maintenance planning based on operating hours and equipment condition rather than relying exclusively on chronological equipment age (Khan et al., 2022). The observed equipment characteristics therefore provided an appropriate empirical setting for evaluating the effectiveness of preventive maintenance under actual construction operating conditions.

Preventive Maintenance was implemented according to a structured maintenance schedule developed from manufacturer recommendations and company maintenance standards, enabling maintenance activities to be performed before critical component failures occurred. Daily inspections were conducted before equipment operation, while lubrication, engine oil replacement, filter replacement, hydraulic inspection, electrical system inspection, cooling system inspection, and undercarriage examination were scheduled according to predetermined operating-hour intervals. This maintenance schedule ensured that routine servicing could be completed without significantly interrupting construction activities because maintenance operations were incorporated into overall project planning. Maintenance records further indicated that servicing activities were documented immediately after completion, providing traceable maintenance histories for every equipment unit throughout the observation period. The preventive maintenance schedule applied during the project is presented in Table 2. The implementation of standardized maintenance intervals follows recommendations provided in manufacturer operation and maintenance manuals to minimize unexpected equipment failures during intensive construction operations (Caterpillar Inc., 2021).

Table 2. Preventive Maintenance Schedule

Maintenance Activity	Service Interval
Daily Inspection	Every day
Greasing	Every 50 operating hours
Engine Oil Replacement	Every 250 operating hours
Oil Filter Replacement	Every 250 operating hours
Fuel Filter Replacement	Every 500 operating hours
Hydraulic System Inspection	Every 500 operating hours
Engine Inspection	Every 1,000 operating hours
Major Overhaul	Every 10,000 operating hours

The maintenance intervals shown in Table 2 demonstrate that preventive maintenance was organized according to the expected degradation characteristics of individual components rather than applying identical servicing intervals to every maintenance activity. Components exposed to continuous friction, contamination, and lubrication degradation were serviced more frequently than structural components with relatively lower deterioration rates. Maintenance personnel reported that adherence to scheduled servicing reduced the occurrence of emergency repairs because minor abnormalities could be detected before developing into major mechanical failures. The systematic recording of inspection results also enabled maintenance decisions to be supported by documented operational evidence instead of relying solely on operator experience. Such maintenance practices correspond with preventive maintenance principles emphasizing planned intervention, systematic inspection, and maintenance documentation as essential elements of equipment reliability management (Wireman, 2005). The integration of scheduled maintenance with maintenance documentation therefore strengthened operational control throughout the construction project.

The observed implementation of Preventive Maintenance indicates that maintenance effectiveness depends not only on compliance with service intervals but also on coordination among operators, mechanics, supervisors, and project management during equipment operation. Routine inspections generated operational information that enabled maintenance personnel to identify lubrication deficiencies, abnormal engine temperatures, hydraulic leakage, and early component wear before these conditions affected equipment productivity. This collaborative maintenance approach reduced uncertainty in maintenance decision-making because inspection findings were consistently supported by maintenance records and equipment operating histories. The integration of operational monitoring with preventive servicing also enhanced maintenance planning by improving spare-part preparation and reducing maintenance response time during scheduled servicing periods. These observations support the view that preventive maintenance should function as an integrated operational management system capable of improving equipment efficiency while minimizing operational interruptions throughout project execution (Akbar et al., 2024). The empirical evidence obtained from this project establishes a foundation for evaluating the quantitative influence of preventive maintenance on downtime, availability, reliability, productivity, and overall equipment effectiveness in the subsequent analysis.

Evaluation of Preventive Maintenance Performance

The effectiveness of the preventive maintenance program was evaluated by comparing the operational performance of heavy equipment before and after its systematic implementation during the observation period. The evaluation focused on changes in downtime, availability, Mean Time Between Failure (MTBF), and Mean Time To Repair (MTTR), as these indicators represent the primary dimensions of equipment maintainability and operational continuity. Operational data were compiled from maintenance logbooks, equipment operating-hour records, and field observation reports to ensure consistency among the analyzed variables. The comparative assessment demonstrated measurable improvements in equipment performance after preventive maintenance activities were implemented according to the predetermined service intervals. These findings indicate that scheduled maintenance contributed to more stable equipment operation by reducing unexpected failures that interrupted construction activities. Such improvements are consistent with systematic maintenance management frameworks that emphasize planned servicing as an effective strategy for improving equipment reliability and operational efficiency (Duffuaa et al., 2000).

Equipment downtime was selected as the first performance indicator because it directly reflects the operational impact of equipment failures on construction activities. Before the implementation of preventive maintenance, downtime was primarily associated with delayed lubrication, engine servicing, hydraulic inspections, and replacement of consumable components that had exceeded their recommended service intervals. Following the implementation of scheduled maintenance, emergency repairs became less frequent and maintenance activities shifted toward planned interventions with shorter service durations. The recorded downtime values during the six-month observation period are presented in Table 3. The monthly comparison indicates a continuous decline in equipment downtime after preventive maintenance became fully integrated into project operations. Similar operational improvements have been reported in construction projects where preventive maintenance successfully minimized unplanned equipment stoppages and enhanced project productivity (Ami & Siallagan, 2026).

Table 3. Equipment Downtime Before and After Preventive Maintenance

Observation Period	Month	Downtime (Hours)
Before Preventive Maintenance	January	26
	February	24
	March	20
After Preventive Maintenance	April	14

May	10
June	8

As shown in Table 3, equipment downtime decreased progressively from 26 hours in January to 8 hours in June, representing a reduction of approximately 69.23% over the observation period. The declining trend demonstrates that scheduled maintenance effectively prevented the accumulation of mechanical defects that commonly develop into major equipment failures requiring lengthy repair times. Field observations also indicated that daily inspections enabled mechanics to identify abnormal engine conditions, hydraulic leakage, and lubrication deficiencies before these issues affected machine operation. Maintenance records further showed that the frequency of corrective maintenance declined after preventive maintenance procedures were consistently implemented according to the established maintenance schedule. These findings support previous studies indicating that preventive maintenance improves equipment availability by reducing failure occurrence and limiting operational interruptions during construction activities (Saputra et al., 2023). The observed reduction in downtime also contributed to more stable construction workflows because equipment remained available throughout critical project operations.

The reduction in downtime was accompanied by improvements in equipment availability and maintenance efficiency, indicating that preventive maintenance enhanced the operational readiness of the heavy equipment fleet. Based on the operational data collected during the final observation period, the calculated Availability reached 98.90%, demonstrating that the equipment remained available for productive operation throughout nearly the entire scheduled working time. The maintenance records also produced an MTBF value of 120 hours, indicating that equipment could operate for relatively long periods before experiencing mechanical failure. At the same time, the calculated MTTR was only 5 hours, suggesting that repair activities were completed efficiently whenever maintenance intervention became necessary. These values indicate that preventive maintenance successfully improved both equipment reliability and maintenance responsiveness by reducing the frequency of failures while shortening repair durations. Maintenance management literature recognizes that simultaneous improvements in Availability, MTBF, and MTTR represent important indicators of effective maintenance planning and execution (Corder, 1992).

Table 4. Availability, MTBF, and MTTR Results

Performance Indicator	Value	Performance Category
Operating Time	720 hours	—
Downtime	8 hours	Low
Availability	98.90%	Excellent
MTBF	120 hours	High
MTTR	5 hours	Excellent

The performance indicators summarized in Table 4 demonstrate that preventive maintenance generated consistent improvements across multiple aspects of equipment operation rather than affecting only a single maintenance variable. High availability indicates that maintenance activities were successfully scheduled without creating excessive planned downtime, while the relatively high MTBF confirms that failures occurred less frequently after maintenance procedures were standardized. The low MTTR further reflects effective maintenance coordination, adequate spare-part preparation, and rapid repair execution when equipment intervention became necessary. The interaction among these indicators illustrates that maintenance effectiveness should be evaluated through an integrated performance framework because operational reliability depends on both equipment durability and maintenance responsiveness. Previous maintenance studies similarly emphasize that continuous monitoring of maintenance indicators provides more reliable information for optimizing maintenance strategies than relying solely on failure frequency or repair costs (Assauri, 2016). The empirical evidence obtained from this study therefore confirms that preventive maintenance substantially improved operational stability and established favorable conditions for enhancing equipment reliability, productivity, and overall operational effectiveness in the subsequent performance analysis.

Heavy Equipment Performance Analysis after Preventive Maintenance

The final stage of the analysis evaluated the influence of preventive maintenance on the overall operational performance of heavy equipment by examining Reliability, Productivity, and Overall Equipment Effectiveness (OEE). These indicators provide a comprehensive assessment because they measure not only the ability of equipment to remain operational but also its capability to sustain productive performance throughout the construction process. The calculated values were derived from operational records collected during the observation period after the preventive maintenance program had been implemented consistently. The results indicate that improvements in maintenance quality were accompanied by measurable gains in equipment efficiency and operational stability. Rather than reflecting isolated maintenance outcomes, these indicators demonstrate the cumulative effect of systematic inspection, timely servicing, and continuous monitoring on equipment performance. Such multidimensional evaluation is widely recommended in construction equipment management because maintenance effectiveness should be interpreted from both technical and operational perspectives (Nakajima, 1988).

Reliability analysis showed that the preventive maintenance program substantially improved the capability of heavy equipment to operate without experiencing unexpected failures during scheduled working periods. Based on the operational data, the calculated Reliability reached 96.00%, indicating that the probability of uninterrupted equipment operation remained very high throughout the observation period. The relatively high reliability value reflects the effectiveness of periodic inspections in identifying component deterioration before mechanical failures occurred. Maintenance personnel reported that early detection of hydraulic leakage, lubrication degradation, and abnormal engine conditions reduced the occurrence of major component failures requiring extensive repair work. These operational findings indicate that preventive maintenance successfully shifted maintenance activities from corrective interventions toward planned servicing based on equipment condition and operating hours. Similar improvements in equipment reliability have been reported in construction maintenance systems implementing Total Productive Maintenance (TPM), where preventive inspection significantly increased equipment availability and operational continuity (Palomino-Valles et al., 2020).

Table 5. Heavy Equipment Performance after Preventive Maintenance

Performance Indicator	Value	Performance Category
Reliability	96.00%	High
Productivity	89.64 m^3/hour	High
Overall Equipment Effectiveness (OEE)	92.03%	World Class

As presented in Table 5, the equipment achieved a productivity value of 89.64 m^3/hour, indicating that the excavator operated efficiently under normal project conditions following routine maintenance implementation. The stable productivity level suggests that scheduled servicing maintained the mechanical condition of critical components, thereby preventing reductions in digging efficiency and cycle-time performance during field operations. Equipment operators also reported smoother machine operation and fewer temporary interruptions caused by overheating, hydraulic instability, or excessive engine vibration after preventive maintenance activities became routine. These observations indicate that equipment productivity is closely associated with maintenance quality because mechanical stability directly influences production capacity and work-cycle consistency. Previous studies similarly concluded that effective equipment maintenance contributes significantly to improving productivity by maintaining equipment performance throughout intensive construction activities (Manikandan et al., 2018). The observed productivity performance therefore demonstrates that preventive maintenance supports both operational efficiency and construction output.

The Overall Equipment Effectiveness (OEE) value obtained in this study reached 92.03%, exceeding the internationally recognized benchmark of 85% commonly associated with World Class equipment performance. This result indicates that the combination of high availability, stable operating performance, and satisfactory work quality enabled the equipment fleet to operate at an excellent efficiency level throughout the project period. The high OEE value also reflects successful coordination between maintenance scheduling, operational planning, and equipment utilization, reducing the performance losses commonly associated with equipment breakdowns and prolonged maintenance activities. Operational documentation confirmed that most scheduled maintenance activities were completed without disrupting daily construction targets, allowing equipment utilization to remain consistently high during the observation period. The integration of preventive maintenance with structured maintenance planning has likewise been recognized as an effective approach for maximizing equipment effectiveness across heavy construction operations (Khan et al., 2022). The findings indicate that preventive maintenance contributes not only to equipment reliability but also to improving overall operational efficiency.

Table 6. Comparison of Heavy Equipment Performance Before and After Preventive Maintenance

Indicator	Before PM	After PM	Improvement
Downtime	26 hours*	8 hours	↓ 69.23%
Availability	96.52%	98.90%	↑ 2.38%
Reliability	92.31%	96.00%	↑ 3.69%
Productivity	84.72 m^3/hour	89.64 m^3/hour	↑ 5.81%
OEE	86.43%	92.03%	↑ 5.60%

The comparative results presented in Table 6 demonstrate consistent improvements across all evaluated performance indicators following the implementation of preventive maintenance. The simultaneous reduction in downtime and increase in Availability, Reliability, Productivity, and OEE indicate that scheduled maintenance generated operational benefits extending beyond equipment repair activities alone. These improvements suggest that preventive maintenance enhanced the interaction between equipment condition, maintenance responsiveness, and production continuity, resulting in more stable construction operations. Similar conclusions have been reported by studies investigating condition-based maintenance, maintenance information systems, operational performance indicators, and workplace organization strategies, all of which emphasize that integrated maintenance management substantially improves equipment efficiency and long-term operational performance (Prabowo et al., 2026; Rosdianto et al., 2026; Aulia & Putri, 2025; Ruiz et al., 2020). From an engineering perspective, the findings reinforce the proposition that preventive maintenance should be considered a strategic operational management approach rather than solely a technical servicing activity. The empirical evidence obtained from this study also supports broader maintenance management theories stating that systematic maintenance planning increases equipment service life, improves project productivity, and enhances resource utilization in construction projects (Dhillon, 2002; Simatupang & Sridharan, 2016; Seeley, 1993).

Engineering Implications and Maintenance Strategy

The findings of this study demonstrate that preventive maintenance should be regarded as a strategic engineering function that directly influences construction project performance rather than as a routine technical activity performed only to prevent equipment failures. The improvements observed in downtime, availability, reliability, productivity, and OEE indicate that maintenance planning contributed to both equipment performance and project execution efficiency. This relationship suggests that maintenance management should be integrated into construction planning from the early stages of project implementation to ensure continuous equipment readiness throughout the project lifecycle. Effective maintenance planning also enables project managers to allocate maintenance resources more efficiently while minimizing disruptions to construction schedules. Such an integrated approach is consistent with maintenance management frameworks emphasizing that operational planning and maintenance activities should be managed as interconnected engineering processes rather than independent functions (Mobley, 2002). The empirical findings therefore reinforce the importance of incorporating preventive maintenance into strategic construction equipment management.

The implementation of preventive maintenance in this study also demonstrates the importance of standardized maintenance procedures supported by systematic operational documentation. Maintenance records collected throughout the project enabled maintenance personnel to monitor equipment conditions continuously, evaluate component deterioration, and determine appropriate servicing intervals based on operational evidence rather than subjective judgement. The availability of complete maintenance histories also facilitated maintenance scheduling because recurring equipment problems could be identified more rapidly during routine inspections. These practices reduced uncertainty in maintenance decision-making and improved coordination between equipment operators, mechanics, and project supervisors. Maintenance information systems have similarly been shown to improve maintenance planning by providing accurate operational data for scheduling and performance evaluation (Aulia & Putri, 2025). The integration of maintenance documentation with field operations therefore represents an important component of sustainable equipment management.

Table 7. Engineering Implications of Preventive Maintenance Implementation

Engineering Aspect	Observed Improvement	Expected Project Impact
Equipment Reliability	Failure frequency decreased	Improved operational continuity
Maintenance Planning	Scheduled servicing implemented consistently	Better maintenance coordination
Equipment Availability	Operational readiness increased	Reduced project delays
Equipment Productivity	Stable production capacity	Higher construction efficiency
Operational Cost Control	Emergency repairs reduced	Lower maintenance expenditure

As presented in Table 7, the engineering implications extend beyond improvements in individual maintenance indicators because preventive maintenance generated operational benefits across multiple dimensions of construction management. The reduction in emergency maintenance activities allowed project resources to be allocated more effectively, while higher equipment availability supported smoother construction workflows throughout the observation period. Stable equipment performance also reduced operational uncertainty by minimizing interruptions associated with unexpected component failures. These outcomes indicate that preventive maintenance contributes to improving both technical performance and managerial decision-making during project execution. Previous studies likewise recognize that structured maintenance systems improve operational performance by optimizing maintenance scheduling and increasing equipment utilization (Prabowo et al., 2026). The observed improvements therefore demonstrate the strategic value of preventive maintenance within construction engineering practice.

From a project management perspective, the study indicates that preventive maintenance supports more efficient utilization of financial and operational resources throughout the construction process. Lower downtime reduced idle equipment hours, enabling equipment utilization rates to remain consistently high during critical construction activities. Maintenance planning also improved spare-part preparation because scheduled servicing created greater predictability regarding component replacement requirements. Such operational predictability contributes to reducing unnecessary inventory while ensuring that essential replacement components remain available when required. Construction equipment management literature emphasizes that effective maintenance scheduling supports resource optimization by balancing maintenance costs against equipment operating performance (Simatupang & Sridharan, 2016). The findings therefore demonstrate that preventive maintenance contributes not only to engineering performance but also to more efficient project resource management.

The present findings also provide practical guidance for construction companies seeking to improve heavy equipment performance through structured maintenance programs. Maintenance activities should be supported by periodic operator training, standardized inspection procedures, digital maintenance records, and continuous monitoring of key maintenance indicators such as Availability, Reliability, MTBF, MTTR, Productivity, and OEE. Integrating these indicators into routine project evaluation enables maintenance decisions to become increasingly data-driven while supporting continuous improvement of maintenance strategies. The adoption of manufacturer-recommended maintenance intervals further strengthens equipment reliability because servicing activities remain consistent with technical specifications throughout equipment operation. These recommendations are aligned with international maintenance management principles emphasizing continuous performance monitoring and preventive intervention to maximize equipment service life (Komatsu Ltd., 2020; Caterpillar Inc., 2021). The engineering benefits observed in this study therefore provide a practical framework for improving maintenance effectiveness in future construction projects.

Although the preventive maintenance program demonstrated measurable operational improvements, several limitations should be acknowledged when interpreting the results. The investigation was conducted within a single road construction project, causing operational conditions, equipment composition, and environmental characteristics to remain relatively homogeneous throughout the observation period. Future studies may strengthen the generalizability of these findings by involving multiple construction projects, longer observation periods, and additional maintenance approaches such as predictive maintenance or condition-based maintenance supported by intelligent monitoring technologies. The integration of sensor-based monitoring, machine learning algorithms, and real-time maintenance analytics also offers promising opportunities for enhancing maintenance decision-making within intelligent construction systems. Emerging developments in digital maintenance technologies indicate that combining preventive maintenance with predictive analytical methods can further improve equipment reliability and operational efficiency in modern construction environments (Khan et al., 2022). These research opportunities provide a valuable direction for advancing intelligent maintenance management while supporting the long-term sustainability of heavy equipment operations in construction projects.

CONCLUSION

This study demonstrates that the implementation of Preventive Maintenance significantly improves the operational performance of heavy equipment used in construction projects through systematic and scheduled maintenance activities. The empirical findings indicate a substantial reduction in equipment downtime following the consistent application of preventive maintenance, enabling heavy equipment to remain available for productive operations throughout the project period. The calculated performance indicators, including an Availability of 98.90%, a Reliability of 96.00%, and an Overall Equipment Effectiveness (OEE) of 92.03%, confirm that the maintenance strategy successfully enhanced equipment readiness, operational reliability, and maintenance efficiency. Improvements in Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) further demonstrate that preventive maintenance effectively reduced failure frequency while enabling faster recovery whenever maintenance interventions were required. Stable equipment conditions also contributed to higher productivity, allowing construction activities to proceed with fewer operational interruptions and more efficient utilization of project resources. These findings confirm that preventive maintenance represents an effective engineering strategy for improving both the technical performance and economic efficiency of heavy equipment in construction projects.

From a practical perspective, the study highlights that preventive maintenance should be incorporated into construction project management as an integral component of operational planning rather than being treated solely as a routine maintenance activity. The integration of scheduled inspections, maintenance documentation, timely component replacement, and systematic monitoring of key performance indicators enables construction companies to optimize equipment utilization while reducing emergency repair costs and minimizing project delays. The results also demonstrate the importance of coordinated collaboration among operators, mechanics, and project managers in maintaining equipment reliability throughout project execution. The use of standardized maintenance procedures and comprehensive maintenance records supports more accurate maintenance scheduling and facilitates continuous performance evaluation. These operational improvements ultimately strengthen project productivity while extending equipment service life and maximizing the return on investment in heavy construction machinery. Consequently, preventive maintenance provides measurable engineering and managerial benefits that contribute to the successful delivery of construction projects.

Future research is encouraged to expand the scope of investigation by involving multiple construction projects, longer monitoring periods, and a wider variety of heavy equipment operating under different environmental and workload conditions. Comparative studies integrating Preventive Maintenance with Reliability Centered Maintenance (RCM), Failure Mode and Effects Analysis

(FMEA), Total Productive Maintenance (TPM), or Condition-Based Maintenance (CBM) may provide a more comprehensive understanding of maintenance optimization strategies for construction equipment. The incorporation of intelligent monitoring technologies, sensor-based condition assessment, and data-driven predictive maintenance models also offers promising opportunities for improving maintenance decision-making in modern construction management. Such developments may further enhance equipment reliability, reduce lifecycle maintenance costs, and support the digital transformation of maintenance systems within intelligent engineering and construction industries. Continuous advancement in maintenance strategies is therefore expected to strengthen both operational resilience and sustainable infrastructure development in increasingly complex construction environments.

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