

EXTENDING THE LIFECYCLE OF TRANSPORT VEHICLES IN A CIRCULAR ECONOMY FRAMEWORK: EVALUATING THE ECONOMIC EFFICIENCY OF MAINTENANCE ACTIVITIES USING THE TOPSIS METHOD

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Abstract: Maintenance plays a vital role in extending the lifespan of transport vehicles, thereby supporting the development of a circular economy in the transportation sector. In Vietnam, however, the potential of maintenance activities has yet to be comprehensively harnessed. This study explores how vehicle lifespans can be prolonged within a circular economy framework by evaluating four maintenance strategies - preventive maintenance (PM), predictive maintenance (PdM), reactive maintenance (RM), and total productive maintenance (TPM) - using the TOPSIS method and five circular economy-oriented criteria. Research indicates that while reactive maintenance is currently the predominant approach in Vietnam due to its lower initial costs, other strategies hold significant potential for facilitating a shift towards more proactive maintenance systems. In particular, Predictive Maintenance (PdM) offers substantial promise by leveraging real-time data analytics to anticipate equipment failures, thereby reducing downtime and maintenance expenses. Such a transition can enhance operational efficiency, extend asset lifespans, and contribute to more sustainable practices in the sector. The study offers practical recommendations for improving maintenance models, reducing resource waste, and advancing circular economy goals. It also acknowledges the current reliance on reactive methods, while emphasizing the long-term benefits and cost-efficiency of proactive alternatives for both businesses and policymakers.

• Keywords: circular economy, transportation vehicles, TOPSIS, lifespan extension, vehicle maintenance.

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Introduction

In the competitive and sustainability-driven transportation industry, optimizing vehicle maintenance is crucial for cost reduction and the promotion of a circular economy. Extending vehicle lifespans, while simultaneously reducing fuel consumption and emissions, generates significant economic and environmental benefits. However, Vietnam's transportation sector faces unique challenges, including an aging vehicle fleet, complex infrastructure, and the increasing impacts of climate change. These factors have prompted governmental initiatives aimed at fostering sustainable transport solutions.

To address these challenges and maximize the benefits of efficient maintenance, various strategies are employed, each with distinct advantages and limitations. Reactive Maintenance (RM), while widely used due to its low initial costs, can lead to higher long-term expenses and operational

disruptions if over-relied upon. Preventive Maintenance (PM) helps reduce breakdown risks but may result in unnecessary interventions and resource consumption. Predictive Maintenance (PdM) optimizes costs through failure forecasting but requires significant technological investment and data accuracy. Total Productive Maintenance (TPM) integrates multiple approaches and emphasizes proactive employee involvement, yet demands strong organizational commitment and substantial resources. No single strategy is optimal in all cases; its effectiveness depends on vehicle types, operational conditions, and available infrastructure.

The impact of maintenance practices extends beyond operational efficiency, playing a crucial role in advancing the circular economy. By extending the operational life of vehicles and their components, effective maintenance directly reduces demand for new manufacturing, thereby conserving valuable natural resources and energy.

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Additionally, optimized maintenance protocols facilitate the reuse and recycling of vehicle parts and materials at the end of their service life, fostering a closed-loop system within the transportation sector. These advancements generate tangible economic benefits, including job creation, reduced operational expenditures, and enhanced transportation reliability and service quality.

Building on this context, the present study evaluates maintenance models commonly employed by Vietnamese transport businesses using the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method. This approach enables a comprehensive assessment of different maintenance strategies and suggests improvements tailored to the specific conditions of Vietnam's transportation sector, aligning with the nation's ongoing transition toward a circular economy. The TOPSIS methodology, a robust multi-criteria decision-making tool, is particularly well-suited for this complex evaluation as it allows for the simultaneous consideration of diverse economic, operational, and sustainability-related factors that influence maintenance strategy selection.

The structure of this study is as follows: Section 2 reviews the relevant literature, followed by Section 3, which outlines the research methodology and data. Section 4 presents and discusses the findings in detail, and Section 5 provides the concluding remarks.

2. Literature Review

Several studies have emphasized the critical role of maintenance in enhancing the operational efficiency of transport vehicles, especially as companies strive to optimize costs and improve reliability.

Mitchell et al. (2002) demonstrated that a well-structured maintenance strategy (preventive maintenance) helps minimize breakdowns and maximize asset utilization. Meanwhile, predictive maintenance (PdM) is gaining popularity due to technological advancements. Simion et al. (2024) analyzed the application of artificial intelligence in predictive maintenance, highlighting its ability to improve vehicle availability and reduce operational disruptions. Mobley (2002) outlined predictive maintenance techniques within the context of total productive maintenance management. Coanda et al. (2020) and Waeyenbergh & Pintelon (2002) emphasized the role of real-time data in developing

accurate and efficient maintenance models like Reactive maintenance.

Total Productive Maintenance (TPM) is a comprehensive approach that integrates various maintenance strategies with active employee participation to enhance operational efficiency. Ahuja & Khamba (2007) assessed TPM implementation initiatives in Indian manufacturing enterprises, highlighting the benefits and challenges of adopting this method. Nakajima (1988), a pioneer in TPM, provided in-depth insights into the theory and application of this methodology in modern maintenance systems.

Numerous studies have employed ranking-based approaches to support decision-making processes. Multi-Criteria Decision-Making (MCDM) methods such as TOPSIS and AHP are commonly applied to optimize the selection of maintenance strategies. For instance, Esfandiari and Rizvandi (2014) used TOPSIS to rank corporate strategies based on multiple evaluation criteria. Similarly, Rivero-Gutiérrez et al. (2021) utilized AHP to facilitate decision-making in transport system management, contributing to the development of more reliable maintenance models. Zhang et al. (2018) also applied TOPSIS to assess the performance of urban public transport priority initiatives.

However, research on vehicle maintenance in the transportation industry, particularly in developing countries like Vietnam, remains limited. Vietnamese transport enterprises face major challenges such as inconsistent infrastructure, limited financial resources, and a lack of comprehensive data on the effectiveness of different maintenance models. Notably, as Vietnam increasingly focuses on sustainable development and the circular economy, existing MCDM approaches have yet to fully integrate key environmental and recycling considerations into maintenance strategy evaluations. This presents a crucial gap in understanding how different maintenance methods contribute to circular economy goals in the transport sector.

This study aims to address that gap by evaluating maintenance models in Vietnamese transport enterprises using the TOPSIS method, thereby proposing adjustments tailored to the country's specific conditions and industry trends. The TOPSIS method, a multi-criteria decision-making technique, is particularly suitable for this research as it allows simultaneous consideration of economic,

operational, and sustainability factors affecting the selection of an optimal maintenance strategy for Vietnamese transport enterprises.

3. Data and research Methodology

Data collection method: The research data for this study were collected through interviews with 12 technical staff from transportation enterprises.

The author conducted direct interviews with technical staff who have expertise and experience in the technical field at transportation companies. Initially, they sought consensus on evaluation and scoring from a group of 10 experts. Subsequently, the author expanded the interviews in two rounds, adding 1 expert in each round, culminating in a total of 12 experts and reaching the highest agreement.

Interview content: The interviews focused on evaluating the current state of vehicle maintenance in Vietnam according to the criteria given by the experts, as well as assessing the weight of these criteria in promoting the circular economy in Vietnam's transportation sectors

Research Method: The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method was employed to evaluate and rank maintenance strategies.

TOPSIS Scoring Matrix

During the analysis, experts assessed maintenance strategies not only based on cost-effectiveness and maintenance efficiency but also on their contributions to the circular economy in the context of Vietnam's transportation industry.

Maintenance Cost (C1): A low-cost maintenance approach helps businesses conserve resources and minimize waste. Strategies with low costs receive high scores (8-10). Conversely, high-cost maintenance approaches requiring expensive spare parts or services are rated lower (1-3) due to their financial burden and resource inefficiency.

Downtime (C2): Maintenance strategies that minimize downtime allow vehicles to resume operation quickly, optimizing resource utilization. Short downtime durations are highly rated (8-10), whereas longer downtimes, which disrupt operations and waste resources, receive lower scores.

Post-Maintenance Failure (C3): This reflects vehicle stability after maintenance. Effective maintenance approaches reduce failures, enhancing vehicle durability and minimizing the need for replacements or additional repairs. Strategies with

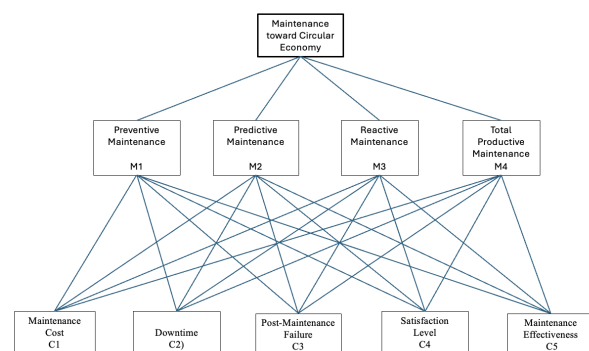
low failure rates receive high scores (8-10), as they ensure long-term operational stability and prevent resource wastage. In contrast, high failure rates lead to additional costs and inefficiencies, earning lower scores (1-3).

Satisfaction Level (C4): This factor evaluates how well a maintenance strategy enhances vehicle performance and service quality. Effective maintenance improves reliability, increases satisfaction levels, and is rated highly (8-10).

Maintenance Effectiveness (C5): This criterion assesses how well a maintenance strategy sustains vehicle stability and durability over time. Highly effective maintenance minimizes the need for frequent repairs or early replacements. Strategies that support long-term performance sustainability receive high scores (8-10), as they contribute to resource conservation and circular economy development.

This study provides insights into optimizing maintenance strategies in Vietnam's transportation sector, offering practical recommendations for enhancing maintenance efficiency, reducing resource waste, and promoting sustainable circular economy practices.

Figure 1. Research's structure



Steps of the TOPSIS Method

+ Constructing the Normalized Matrix

Normalization is applied to the values using the following formula to transform them onto a common scale for comparability:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^n x_{ij}^2}} \quad (1)$$

r_{ij} : is the normalized value of element x_{ij}

x_{ij} : is the original value of criterion j in dataset i .

+ Calculating the Weighted Normalized Matrix

Each criterion is weighted based on its assigned

level of importance, and the weighted normalized values are then calculated using the specified formula:

$$v_{ij} = w_j \cdot r_{ij}$$

v_{ij} : is the weighted normalized value for criterion j of option i.

w_j : is the weight assigned to criterion j, reflecting its importance in the final decision

r_{ij} : is the normalized value of element j in dataset i.

+ Determining the Ideal and Non-Ideal Solutions

Ideal solution (A⁺): The best value for each criterion.

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\}$$

Non-ideal solution (A⁻): The worst value for each criterion

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\}$$

+ Calculating the Distance to the Ideal and Non-Ideal Solutions

$$D_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (2)$$

$$D_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (3)$$

+ The closeness coefficient (Ci)

Ci is calculated to determine the relative closeness of each alternative to the ideal solution.

The preference score is obtained using the following formula:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (4)$$

A higher Ci value indicates a more preferred alternative.

+ Analyzing results and drawing conclusions

Based on the computed values, the best maintenance strategy can be determined, leading to a well-informed decision

4. Research Results

The values in the matrix are derived from ratings provided by experts in the Vietnamese transportation sector, who evaluated the maintenance options based on real-world operational considerations. These experts assessed each maintenance strategy in terms of its effectiveness and alignment with the

operational challenges and economic realities within Vietnam.

Table 1: Initial TOPSIS Matrix

Option	Maintenance Cost (C1)	Downtime (C2)	Failure Rate (C3)	Business Satisfaction (C4)	Maintenance Effectiveness (C5)
Preventive Maintenance (M1)	7	6	5	7	6
Predictive Maintenance (M2)	5	3	4	9	8
Reactive Maintenance (M3)	8	7	7	5	4
Total Productive Maintenance (M4)	6	4	3	8	7

Source: Compiled from the survey

Preventive Maintenance (M1): This maintenance strategy is characterized by its reasonable maintenance costs. However, it faces challenges such as longer vehicle downtime and higher failure rates, which negatively impact the long-term operational efficiency of the vehicles.

Predictive Maintenance (M2): This option stands out for its superior maintenance effectiveness and high business satisfaction levels, which promote the long-term operational viability of vehicles, aligning with the goals of a circular economy. Predictive Maintenance, despite requiring substantial initial investment in advanced technology and data infrastructure, demonstrates significantly reduced vehicle downtime and lower failure rates.

Reactive Maintenance (M3): Reactive Maintenance scores well in terms of low maintenance costs and moderate downtime; however, it suffers from lower maintenance effectiveness and requires more frequent interventions.

Total Productive Maintenance (M4): While M4 scores high on business satisfaction, it is associated with considerable failure rates and extended vehicle downtime, which adversely affect its economic efficiency.

Based on the comprehensive evaluation provided by the Vietnamese experts, the Initial Decision Matrix is as follows:

+ Initial Decision Matrix

$$D = \begin{bmatrix} 7 & 6 & 5 & 7 & 6 \\ 5 & 3 & 4 & 9 & 8 \\ 8 & 7 & 7 & 5 & 4 \\ 6 & 4 & 3 & 8 & 7 \end{bmatrix}$$

+ Normalized Matrix Using Eq (1)

$$R = \begin{bmatrix} 0.5307 & 0.5721 & 0.5025 & 0.4730 & 0.4671 \\ 0.3790 & 0.2860 & 0.4020 & 0.6082 & 0.6228 \\ 0.6065 & 0.6674 & 0.7035 & 0.3379 & 0.3114 \\ 0.4549 & 0.3814 & 0.3015 & 0.5406 & 0.5449 \end{bmatrix}$$

+ Weighted Normalized Matrix

Table 1. Weighted criteria

Criteria	Symbol	Weight (W)	Rationale
Maintenance Efficiency	C5	0.4	Most important due to its impact on vehicle durability, reducing resource waste in the Circular Economy (CE).
Failure Rate	C3	0.3	Helps reduce indirect costs and increases vehicle sustainability.
Downtime	C2	0.15	Affects vehicle utilization efficiency, but not the most critical factor in CE.
Enterprise Satisfaction	C4	0.1	Important for ensuring the feasibility of implementing circular maintenance.
Maintenance Cost	C1	0.05	Lower weight because CE focuses more on resource optimization than short-term cost savings.

Source: Expert Survey

Therefore, the expert-weighted vector $W = [0.01, 0.15, 0.3, 0.1, 0.4]$, and the weighted normalized matrix is:

$$V = \begin{bmatrix} 0.0265 & 0.0572 & 0.1508 & 0.0710 & 0.1868 \\ 0.0190 & 0.0286 & 0.1206 & 0.0912 & 0.2491 \\ 0.0303 & 0.0667 & 0.2111 & 0.0507 & 0.1246 \\ 0.0227 & 0.0381 & 0.0905 & 0.1811 & 0.2180 \end{bmatrix}$$

+ Ideal and Non-Ideal Solutions

$$A^+ = [0.0303, 0.0667, 0.2111, 0.0912, 0.2491]$$

$$A^- = [0.0190, 0.0286, 0.0905, 0.0507, 0.1246]$$

+ Euclidean Distance to Ideal and Non-Ideal Solutions Using Eq(2), Eq(3)

$$D^+ = [0.0896, 0.0988, 0.1309, 0.1284]$$

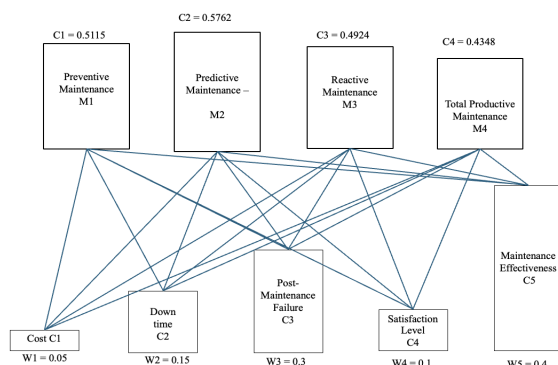
$$D^- = [0.0938, 0.1343, 0.1270, 0.0988]$$

+ Preference Value C_i using Eq (4)

$$C = [0.5115, 0.5762, 0.4924, 0.4348]$$

+ Ranking of Maintenance Options

Figure 1. Research's results



Source: Designed by the author

$C2 \approx 0.5762$: M 2 (Predictive Maintenance) is the most optimal.

$C1 \approx 0.5115$: M 1 (Preventive Maintenance) ranks second.

$C3 \approx 0.4924$: M 3 (Reactive Maintenance) ranks third.

$C4 \approx 0.4348$: M 4 (Total Productive Maintenance) has the lowest score.

The evaluation results indicate that **Predictive Maintenance (C2)** is the most optimal approach, receiving the highest priority score of approximately 0.5762. This reflects its strong potential in addressing the operational challenges of Vietnam's aging and overused vehicle fleet.

Predictive Maintenance (M2) and potential in the context of aging and over-exploited vehicles:

Despite the higher technological and skill requirements of Predictive Maintenance, its top ranking indicates an anticipation of its potential to address the inherent challenges of Vietnam's aging vehicle fleet:

Maximizing the useful lifespan of older vehicles:

For vehicles that have been in service for many years and potentially subjected to over-exploitation, Predictive Maintenance can facilitate the early detection of latent degradation, enabling timely interventions to extend their operational lifespan, rather than premature disposal. This directly contributes to the more efficient use of resources, a core tenet of the circular economy.

Mitigating unexpected failures from over-exploitation: Continuous monitoring of operational conditions through Predictive Maintenance can provide early warnings of failure risks arising from overloading or improper operation, thereby reducing sudden breakdowns that cause costly disruptions and optimizing the utilization of existing vehicles.

Optimizing spare part utilization for older models:

Accurately determining the timing and type of spare parts needed through Predictive Maintenance can help avoid "just-in-case" replacements or the use of unsuitable parts for older vehicles, ensuring performance and safety while promoting the repair and reuse of components whenever feasible, aligning with circular economy principles.

Preventive Maintenance (M1) and its foundational role in a developing maintenance system:

The second-place ranking of Preventive Maintenance underscores the importance of basic procedures, especially within a maintenance system that is still developing:

Establishing minimum standards: Preventive Maintenance provides a fundamental framework for vehicle care, helping to ensure essential maintenance

activities are performed, even with limited technical expertise and equipment. This helps maintain a minimum level of safety and operational efficiency for the aging fleet.

Preventing common failures: Even with a less professional maintenance system, adherence to preventive maintenance schedules can help prevent common failures due to normal wear and tear, reducing the burden on reactive repair efforts.

Reactive Maintenance (M3) and its clear limitations in the Vietnamese context:

The lower ranking of Reactive Maintenance, despite its current prevalence, highlights its inadequacies in addressing the challenges of an older, over-exploited fleet:

Increased risk of severe damage in older vehicles: Relying solely on fixing breakdowns as they occur can lead to the accumulation of minor issues, causing more significant and costly failures in vehicles that are in a state of structural aging and operational degradation.

Frequent operational disruptions due to lack of prediction: Dependence on reactive repairs results in unpredictable downtime, impacting transportation efficiency and increasing opportunity costs, especially in a context of continuous transport demands.

Hindrance to optimizing the lifecycle of older vehicles: Reactive maintenance does not encourage proactively extending vehicle lifespans or planning for efficient parts replacement, contradicting the principles of the circular economy.

Total Productive Maintenance (M4) and implementation challenges with limited resources:

The lowest ranking of Total Productive Maintenance reflects the difficulties in implementing such a complex and resource-intensive system in the current Vietnamese context:

Significant investment required in training and technology: Effective TPM implementation demands a highly skilled workforce and the support of advanced management technologies, which can be a major barrier for many small and medium-sized transport enterprises with limited resources.

Difficulty in changing maintenance culture: TPM requires the participation and responsibility of all departments, which can take considerable time to build and sustain in an environment where

a proactive maintenance culture is not yet strongly established.

5. Conclusions and recommendations

This study applied the TOPSIS multi-criteria decision-making method to evaluate the economic efficiency and other aspects of four vehicle maintenance strategies in the context of Vietnam's aging transportation fleet and growing emphasis on circular economy principles. The findings clearly indicate that Predictive Maintenance (M2), with the highest score of 0.5762, is considered the most optimal approach. This result reflects a growing recognition among experts of the long-term economic and operational advantages of proactive, data-driven maintenance methods.

In alignment with the goals of a circular economy, Predictive Maintenance demonstrates superior potential to extend the operational lifecycle of vehicles, reduce waste, and optimize resource use through early detection of faults and condition-based interventions. While Preventive Maintenance (M1) (score: 0.5115) remains foundational in settings with limited technical capacity, and Reactive Maintenance (M3) (score: 0.4924) may still serve short-term needs, both are less effective in achieving lifecycle optimization. Total productive maintenance (M4), despite its holistic nature, ranks lowest (0.4348), reflecting practical limitations such as high implementation costs and required technical infrastructure.

Key recommendations for Circular Economy integration:

First, investing in enabling technologies forms the foundation for modernizing maintenance practices in Vietnam's transport sector. Developing digital infrastructure, such as sensors, telematics, and real-time data analytics, is particularly critical for aging fleets that are prone to mechanical failures due to overuse. In the short term, implementing low-cost retrofit kits and mobile diagnostics allows operators to improve vehicle performance and reduce unexpected downtimes. In the long term, the integration of smart, interconnected systems will facilitate lifecycle optimization and predictive asset management. Such technological advancement directly contributes to circular economy objectives by extending vehicle lifespan, reducing material consumption, and minimizing maintenance-related waste.

Second, enhancing human capital and management capacity is essential to operationalize

advanced maintenance systems. In the context of Vietnam, where technical personnel in transport operations often lack specialized diagnostic skills, targeted upskilling through practical workshops provides immediate benefits. Over the longer term, the establishment of formal education programs and professional certifications in predictive maintenance will ensure a skilled and sustainable workforce. This not only increases operational efficiency but also supports circular practices by enabling more effective resource use and reducing the frequency of vehicle retirement due to avoidable failures.

Third, a strategic shift from reactive to predictive maintenance models must be pursued. While reactive approaches remain necessary for unforeseen breakdowns, they often result in excessive costs and wasted resources. In the short term, hybrid strategies that combine basic predictive checks with traditional repairs can help mitigate risks for overutilized fleets. Over time, predictive maintenance should become the dominant model, allowing for proactive interventions that prevent major failures. This transition enhances resource efficiency by optimizing asset utilization and aligns with circular economy principles through reduced material input and extended service life of transport assets.

Fourth, supportive policy frameworks and incentive mechanisms are crucial, particularly for small and medium-sized operators managing older vehicles. In the short run, governments should provide financial incentives such as tax relief and subsidies for installing monitoring technologies. In the long term, integrating predictive maintenance standards into national transport regulations will encourage widespread adoption. Such policy interventions are vital in embedding circular economy thinking across the sector by promoting resource efficiency, reducing emissions from poorly maintained fleets, and discouraging premature scrapping.

Fifth, fostering cross-sector collaboration and knowledge exchange enhances solution relevance and scalability. Collaboration between transport operators, technology providers, and research institutions facilitates the development of context-appropriate, cost-effective predictive maintenance solutions. Short-term pilot projects can demonstrate the tangible benefits of these practices, building stakeholder confidence. In the long run, sustained partnerships in research and development will drive innovation and enable systematic circular transformation through the sharing of best practices,

technological refinement, and continuous feedback loops.

Finally, integrating predictive maintenance into lifecycle strategies is key to maximizing asset value and minimizing waste. In the short term, data derived from predictive diagnostics can inform decisions on whether to refurbish, repurpose, or retire vehicles based on actual condition rather than estimated timelines. Over the long term, fully integrated lifecycle management systems will allow for dynamic and data-driven decisions that optimize resource use across each phase of a vehicle's life. This strategic alignment strengthens the transport sector's contribution to a circular economy by ensuring that assets are maintained, upgraded, and recycled systematically rather than discarded prematurely.

By adopting these six strategies - tailored to the Vietnamese transport context - the sector can transition from a resource-intensive model to one that is resource-efficient and circular.

While this study provides a structured evaluation of maintenance strategies within Vietnam's transport sector, several limitations should be acknowledged. The reliance on expert-based scoring and weighting introduces a degree of subjectivity, which may affect the robustness of the final rankings. Furthermore, the analysis is context-specific and may not be generalizable beyond Vietnam's fragmented and aging transport systems.

References:

- Ahuja, I. S., & Khamba, J. S. (2007). An evaluation of TPM implementation initiatives in an Indian manufacturing enterprise. *Journal of Quality in Maintenance Engineering*, 13(4), 338-352. <https://doi.org/10.1108/13552510710829443>
- Coanda, P., Avram, M., & Constantin, V. (2020). A state of the art of predictive maintenance techniques. *IOP Conference Series: Materials Science and Engineering*, 997(1), 012039. <https://doi.org/10.1088/1757-899X/997/1/012039>
- Esfandiari, M., & Rizvandi, M. (2014). An application of TOPSIS method for ranking different strategic planning methodologies. *International Journal of Industrial Engineering Computations*, 4(7). <https://doi.org/10.5267/j.msl.2014.6.022>
- Mitchell, E., Robson, A., & Prabhu, V. B. (2002). The impact of maintenance practices on operational and business performance. *Managerial Auditing Journal*, 17(5), 234-240. <https://doi.org/10.1108/02686900210429641>
- Mobley, R. K. (2002). 6 - Predictive Maintenance Techniques. In *An Introduction to Predictive Maintenance (Second Edition)* (pp. 99-113). Butterworth-Heinemann. <https://doi.org/10.1016/B978-075067531-4/50006-3>
- Nakajima, S. (1988). *Introduction to TPM: Total Productive Maintenance*. Productivity Press.
- Omer, M. A. E., Ibrahim, A. M. M., Elsheikh, A. H., & Hegab, H. (2025). A framework for integrating sustainable production practices along the product life cycle. *Environmental and Sustainability Indicators*, 26, 100606. <https://doi.org/10.1016/j.indic.2025.100606>
- Rivero-Gutiérrez, L., De Vicente Oliva, M. A., & Romero-Ania, A. (2021). Managing Sustainable Urban Public Transport Systems: An AHP Multicriteria Decision Model. *Sustainability*, 13(9), 4614. <https://doi.org/10.3390/su13094614>
- Simion, D. I., Postolache, F., Fleacă, B., & Fleacă, E. (2024). AI-driven predictive maintenance in modern maritime transport-enhancing operational efficiency and reliability. *Applied Sciences*, 14(20), 9439. <https://doi.org/10.3390/app14209439>
- Waeyenbergh, G., & Pintelon, L. (2002). A framework for maintenance concept development. *International Journal of Production Economics*, 77(3), 299-313. [https://doi.org/10.1016/S0925-5273\(01\)00156-6](https://doi.org/10.1016/S0925-5273(01)00156-6)
- Zhang, X., Zhang, Q., Sun, T., & Zou, Y. (2018). Evaluation of urban public transport priority performance based on the improved TOPSIS method: A case study of Wuhan. *Sustainable Cities and Society*, 43(1). <https://doi.org/10.1016/j.scs.2018.08.013>