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Optimization of Railway Bridge Maintenance Needs Through Performance-Based Policy Evaluation

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ABSTRACT

Railway bridge maintenance in Indonesia faces severe budgetary constraints, resulting in inadequate upkeep of aging infrastructure and heightened safety risks. This study evaluates existing maintenance policies, estimates associated costs, and proposes optimization strategies by combining policy analysis, cost-benefit evaluation, and evaluative methods. Focusing on bridges in the Jakarta area, the research uses technical data on bridge age and structural conditions to project a 2025 maintenance cost of Rp7.09 billion. The cost-benefit analysis confirms financial feasibility, as the Net Present Value (NPV) remains positive across multiple discount rate scenarios. The study recommends risk-based regulatory revisions for old bridges and disaster-prone areas, the use of predictive technologies such as IoT, AI, and drones to reduce inspection costs, and innovative financing through public–private partnerships and endowment funds. Additional measures include climate-resilient design standards, prefabricated components, and academic collaboration for cost-effective innovation. Findings demonstrate that risk-based asset management, technological integration, and multi-stakeholder coordination are essential to achieving sustainable and financially viable maintenance. The proposed framework not only supports Indonesia's railway resilience and safety but also offers a replicable model for other emerging economies facing similar fiscal and infrastructure challenges.
Keywords: *railway bridge maintenance, cost-benefit analysis.*

ABSTRAK

Pemeliharaan jembatan kereta api di Indonesia menghadapi keterbatasan anggaran yang parah, yang mengakibatkan perawatan infrastruktur yang menua tidak memadai dan meningkatkan risiko keselamatan. Penelitian ini mengevaluasi kebijakan pemeliharaan yang ada, memperkirakan biaya terkait, dan mengusulkan strategi optimisasi dengan menggabungkan analisis kebijakan, evaluasi biaya-manfaat, dan metode evaluatif. Dengan fokus pada jembatan di wilayah Jakarta, penelitian ini menggunakan data teknis tentang usia jembatan dan kondisi struktural untuk memproyeksikan biaya pemeliharaan tahun 2025 sebesar Rp7,09 miliar. Analisis biaya-manfaat menegaskan kelayakan finansial, karena Nilai Bersih Sekarang (NPV) tetap positif di berbagai skenario tingkat diskonto. Studi ini merekomendasikan revisi regulasi berbasis risiko untuk jembatan tua dan daerah rawan bencana, penggunaan teknologi prediktif seperti IoT, AI, dan drone untuk mengurangi biaya inspeksi, serta pembiayaan inovatif melalui kemitraan publik–swasta dan dana abadi. Langkah-langkah tambahan meliputi standar desain yang tahan iklim, komponen prefabrikasi, dan kolaborasi akademik untuk inovasi yang hemat biaya. Hasil penelitian menunjukkan bahwa manajemen aset berbasis risiko, integrasi teknologi, dan koordinasi multi-pemangku kepentingan sangat penting untuk mencapai pemeliharaan yang berkelanjutan dan layak secara finansial. Kerangka kerja yang diusulkan tidak hanya mendukung ketahanan dan keselamatan perkeretaapian Indonesia tetapi juga menawarkan model yang dapat ditiru untuk ekonomi negara berkembang lainnya yang menghadapi tantangan fiskal dan infrastruktur serupa.
Kata kunci: pemeliharaan jembatan kereta api, analisis biaya-manfaat.

1. INTRODUCTION

Railway bridges play a crucial role in supporting connectivity and ensuring the smooth operation of railway transportation in Indonesia. The increasing demand for rail services and the aging of existing infrastructure have made maintenance activities more urgent. However, limited government budgets and competing priorities, such as the construction of new lines or the purchase of rolling stock, have resulted in insufficient attention to bridge maintenance. Consequently, many railway bridges in Indonesia face structural deterioration that threatens safety, disrupts train operations, and increases overall maintenance costs.

Previous studies on infrastructure management have emphasized the importance of systematic maintenance strategies, including life-cycle cost analysis, asset management frameworks, and cost-benefit analysis (CBA) for prioritizing investments in public works. Research in developed countries has shown that predictive maintenance approaches, supported by technologies such as IoT and AI, can reduce inspection costs and enhance cost efficiency. Similarly, studies in the field of infrastructure financing highlight the role of innovative mechanisms, including public–private partnerships and endowment funds, in addressing budgetary limitations. However, in the context of developing countries, particularly Indonesia, the integration of CBA into railway bridge maintenance policy remains underexplored.

This gap indicates that while CBA is a well-established tool for evaluating infrastructure projects, its application to inform specific maintenance policies for railway bridges in Indonesia considering the unique challenges of limited budgets, regulatory constraints, and structural vulnerability has not been sufficiently addressed. A more comprehensive and evidence-based approach is therefore needed to ensure sustainable maintenance practices that balance cost efficiency with structural safety.

The objective of this study is to evaluate existing railway bridge maintenance policies in Indonesia, estimate associated costs, and propose optimization strategies through policy analysis and cost-benefit evaluation. By bridging the gap between technical cost analysis and policy decision-making, this research contributes to the development of a performance-based policy framework that supports sustainable railway infrastructure management in Indonesia and provides insights applicable to other emerging economies. The study applies a policy analysis approach combined with cost-benefit analysis and evaluative methods, focusing on railway bridges in the Jakarta metropolitan area that play a vital role in the public transportation system. The location was selected due to its high operational density and the strategic importance of the bridges in the railway network. Several bridges in Jakarta and West Java with diverse characteristics are analyzed to obtain a representative picture of urban railway bridge

management. The main scope of the research includes bridge maintenance, cost needs analysis, and the evaluation of railway infrastructure management policies.

Table 1. List of relevant previous research

Author	Ttile	Objective	Result
(Lu & Cai, 2020)	Overview on safety management and maintenance of high-speed railway in China	analyze the safety management system and maintenance strategies applied to the high-speed rail network (HSR) in China, with a focus on the integration of policies, technology, and human resources	The results show that China's success in managing HSR is supported by an integrated safety management system that combines strict regulations from the National Railway Administration (NRA), real-time monitoring technology (such as vibration sensors and AI for rail fault detection), as well as high-quality HR training
(Liljenström et al., 2022)	Including maintenance in life cycle assessment of road and rail infrastructure—a literature review	to assess the extent to which maintenance activities are integrated into the Life Cycle Assessment (LCA) of road and rail infrastructure through a literature review	The review emphasizes that integrating maintenance into LCAs is essential for sustainable decisions in infrastructure planning
(Shang et al., 2023)	Systems thinking approach for improving maintenance management of discrete rail assets: a review and future perspectives	Analyze the application of *Systems Thinking* in railway asset maintenance management	Traditional approaches tend to be fragmented and give less consideration to systemic interactions, while systems *thinking* integration (such as dynamic modeling, feedback analysis, and multidisciplinary approaches) can improve maintenance efficiency, risk prediction, and asset sustainability
(Bianchi et al., 2025)	Systematic review railway infrastructure monitoring: From classic techniques to predictive maintenance	evaluate the development of railway infrastructure monitoring methods through systematic reviews, ranging from classical techniques (such as visual inspection and conventional sensors) to predictive approaches based on advanced technologies (AI, IoT, big data), with a focus on identifying advantages, limitations, and gaps in implementation.	reveals that conventional techniques are still dominant but less efficient in detecting early failures, while predictive methods improve accuracy and reduce downtime through real-time data analysis.

Author	Ttile	Objective	Result
(Hamer et al., 2022)	An overview of strategic bridge life cycle modelling on the British Railway	explores strategic approaches in modelling the life cycle of railway bridges in the UK, with a focus on optimising the cost, maintenance and reliability of infrastructure.	The implementation of lifecycle-based strategies can help reduce long-term maintenance costs, improve operational safety, and support the sustainability of the railway system through more informed decisions in bridge management
(Gkoumas et al., 2021)	Research in bridge maintenance, safety and management: An overview and outlook for europe	to review research developments in bridge maintenance, safety and management in Europe and identify future challenges and opportunities	The integration of technologies such as smart sensors, artificial intelligence, and real-time data analysis has the potential to improve bridge maintenance efficiency and safety
(Shahrivar et al., 2025)	AI-based bridge maintenance management: a comprehensive review	to review the role of artificial intelligence (AI) in bridge maintenance management, with a focus on improving efficiency, inspection accuracy, and data-driven decision-making	The application of AI in bridge maintenance can improve the accuracy of damage diagnosis, reduce operational costs, and extend the service life of infrastructure

Source: Analysis, 2025

Previous research on bridge maintenance has predominantly emphasized technical aspects such as structural analysis, material performance, and inspection methods—without integrating these elements into broader policy and budgetary frameworks. Consequently, there remains a limited understanding of how governmental regulations, including those issued by the Ministry of Public Works and Housing (PUPR) or the Ministry of Transportation, influence the effectiveness and prioritization of railway bridge maintenance programs. Furthermore, existing studies on infrastructure budget optimization commonly adopt static models based on historical cost analysis, failing to capture dynamic factors such as maintenance demand fluctuations, structural failure risks, and the long-term effects of climate change. The absence of risk-based budgeting and predictive modeling frameworks restricts the capacity to design adaptive and efficient allocation strategies.

In addition, the evaluation of railway infrastructure maintenance policies continues to rely primarily on macro-level financial data (e.g., national or regional budgets) rather than micro-level operational data such as bridge usage frequency, geographic conditions, or traffic loads. This imbalance limits the precision and comprehensiveness of policy assessments, particularly in terms of cost-effectiveness measurement. Finally, the currently available budget models are insufficiently responsive to external variables such as regulatory shifts, inflation, or

natural disasters, resulting in frameworks that are less adaptable to the evolving demands of long-term infrastructure management.

2. METHOD

This study adopts a mixed-method approach combining policy analysis and cost-benefit analysis (CBA) to evaluate railway bridge maintenance strategies in Indonesia. The methodological steps are as follows:

2.1 Data Collection

The research focuses on selected railway bridges in the Jakarta metropolitan area and parts of West Java, which were chosen due to their high traffic density and critical role in the railway network. Data sources include:

a. Government documents: Ministry of Transportation reports, Directorate General of Railways maintenance budgets (2018–2024), and Indonesian National Railway Company (KAI) technical reports.
b. Technical inspection data: Bridge condition surveys, structural age profiles, and maintenance history obtained from railway operator records.
c. Secondary data: Accident statistics, traffic volume data, and cost benchmarks from academic literature and international case studies.

2.2 Policy Analysis

Policy analysis was conducted using qualitative content analysis of regulatory documents (e.g., PUPR guidelines, Ministry of Transportation decrees) and railway operator policies. In addition, expert consultations with engineers and policymakers were carried out to evaluate the alignment between technical needs and budget allocations. The analysis focused on identifying gaps in risk-based asset management, financing schemes, and integration of predictive technologies.

2.3 Cost-Benefit Analysis (CBA)

The Cost–Benefit Analysis (CBA) framework was employed to assess the economic feasibility of various bridge maintenance strategies. The analysis incorporated both cost and benefit components derived from empirical and policy-based data. The cost component included direct maintenance expenditures such as inspection, repair, and rehabilitation activities, which were estimated using government budget allocations and contractor cost norms. The benefit component consisted of three major elements: avoided accident costs, calculated based on the probability of accidents multiplied by the average cost of damage per incident; extended asset life, represented by the avoided replacement costs resulting from an

extended bridge service life of approximately 10–15 years; and operational efficiency, measured through reductions in train delays and service disruptions, and monetized in terms of passenger time savings and freight transport efficiency.

To ensure robustness, a sensitivity analysis was performed using discount rates of 5%, 7%, and 10%, in accordance with Indonesian infrastructure project appraisal standards. The Net Present Value (NPV) and Benefit–Cost Ratio (BCR) were subsequently computed to determine the financial viability and prioritize the most economically advantageous maintenance alternatives.

2.4 Analytical Framework

The methodological process is illustrated in Figure 1, which outlines the research flow:

1. Identification of problem (budgetary constraints and maintenance backlog).
2. Data collection (technical, financial, regulatory).
3. Policy analysis (content review and expert validation).
4. Cost-benefit analysis (quantification of costs and benefits).
5. Evaluation of policy alternatives and recommendations.

This approach ensures both quantitative economic assessment and qualitative policy evaluation, making the results reproducible and academically rigorous.

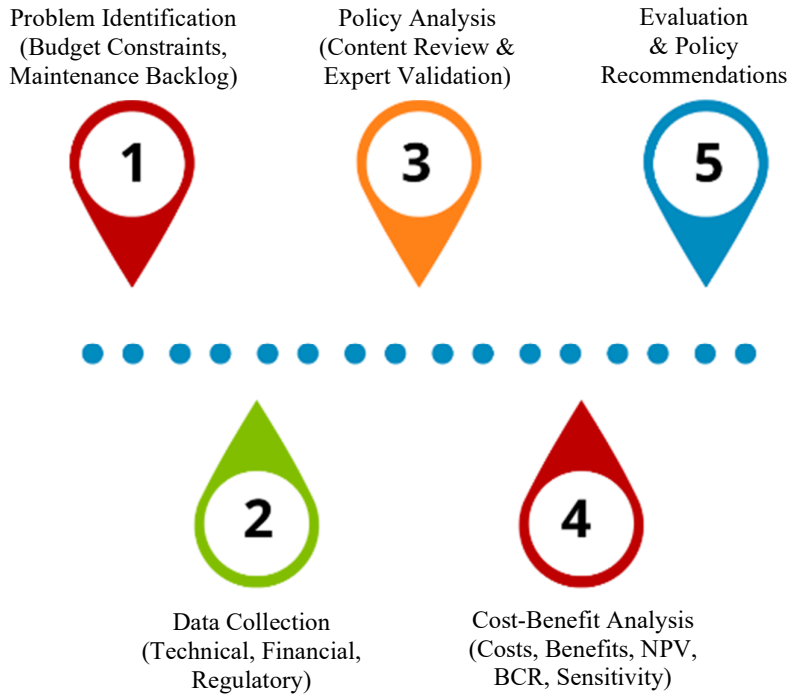

Figure 1. Flowchart policy analysis methods
Source: Documentation, 2025

3. RESULT AND DISCUSSION

Policy analysis for railway bridge maintenance needs to be carried out. The policy analysis method is based on the problems that occur. The government's policy for railway bridge maintenance has a good aspect of regulatory strength. Although there are still shortcomings of regulations and implementation challenges in the future, such as:

1. Ambiguity in technical provisions
2. Weak sanctions and law enforcement
3. Lack of regulatory support for advanced technologies
4. Absence of climate-resilient standards
5. Dependence on the State Budget (APBN).

These constraints limit the ability to implement proactive and risk-based maintenance strategies.

Figure 2. Railway bridge in Jakarta
Source: Documentation, 2025

Based on the Ministry of Transportation Regulation PM 59/2023, the estimated railway bridge maintenance cost for 2025 is Rp 7.09 billion, which includes personnel, equipment, and materials. Table 2 details the breakdown of direct maintenance costs.

Table 2. Details of bridge maintenance costs

No	Job Description	Unit	Volume	Unit Price (Rp.)	Total Price (Rp.)
1	Spot Repair Painting	m^2	5013	316.035,07	1.584.283.806
2	Channel Normalization	m^3	5109	873.117,26	4.460.756.081
3	Wisdom Building Grass Cutting	m^2	425.726	2458,10	1.046.477.081
				Total	**7.091.516.968**

Source: Analysis 2025

The CBA shows that the NPV is consistently positive (Rp 2.17–2.90 billion across years 0–5, at a 6% discount rate). This indicates that the project is financially feasible, as benefits (avoided accident costs, extended asset life, reduced disruption) outweigh costs. Here is a table showing the present *value (PV)* of costs and benefits as well as *Net Present Value (NPV)* from year 0 to year 5 with a discount rate of 6%:

Table 3. PV and NPV value

Year	PV Cost (Rp)	PV Benefits (Rp)	NPV (Rp)
0	7.091.516.968	10.000.000.000	2.908.483.032
1	6.690.110.350	9.433.962.264	2.743.851.914
2	6.311.424.859	8.899.964.405	2.588.539.546
3	5.954.173.443	8.396.193.782	2.442.020.339
4	5.617.146.641	7.920.937.533	2.303.790.892
5	5.299.194.012	7.472.581.729	2.173.387.716

Source: Analysis 2025

If the NPV > 0, the project is economically viable.

Sensitivity analysis was conducted to see how changes in discount rates affect the *Net Present Value (NPV) of* railway bridge maintenance projects. Table 4 illustrates the sensitivity of NPV to discount rates. Even at 10%, the NPV remains positive (Rp 13.93 billion), showing the robustness of railway bridge maintenance investments. However, the decreasing NPV trend indicates vulnerability to higher financing costs or interest rate fluctuations.

Table 4. NPV scenario

Discount Rate (%)	Total PV Cost (Rp)	Total PV Benefit (Rp)	Total NPV (Rp)
4%	38.661.690.000	54.518.220.000	15.856.530.000
6%	36.963.570.000	52.123.640.000	15.160.070.000
8%	35.405.890.000	49.927.100.000	14.521.210.000
10%	33.973.950.000	47.907.870.000	13.933.920.000

Source: Analysis 2025

As the discount rate increases from 4% to 10%, the present value of benefits and costs decreases. The NPV remains positive in all scenarios, indicating that the project is still viable despite the change in discount rates. However, the higher the discount rate, the smaller the NPV, which means the project becomes less financially attractive if interest rates or capital costs increase.

The findings confirm the initial hypothesis that integrating policy reform with cost optimization can effectively address existing gaps in railway bridge maintenance. Although the financial feasibility is supported by a positive Net Present Value (NPV), implementation remains constrained by policy-related weaknesses such as limited regulatory enforcement and dependence on the national budget (APBN). Therefore, a transition toward risk-based and

performance-based asset management frameworks is essential to ensure long-term sustainability and operational resilience.

The Cost–Benefit Analysis (CBA) results indicate that the economic benefits of bridge maintenance outweigh the associated costs, reinforcing the importance of prioritizing preventive maintenance to minimize future rehabilitation expenses and reduce accident risks. Sensitivity analysis further reveals that higher discount rates decrease NPV values, suggesting the need for governments and railway operators to pursue low-interest financing mechanisms—such as public–private partnership (PPP) schemes or asset recycling—to maintain project profitability. Maintenance prioritization should also be guided by a comprehensive risk assessment that considers bridge age, corrosion rate, traffic load, and the potential economic losses in the event of structural failure.

Moreover, the integration of advanced technologies, including vibration monitoring sensors and artificial intelligence (AI) for early damage detection, can significantly improve cost efficiency and extend asset service life without incurring sudden large-scale expenditures. Given that the benefits of bridge maintenance extend to multiple stakeholders—including railway operators, government agencies, and the logistics industry—a collaborative financing framework is recommended. This may include user-based charges, tax incentives for infrastructure investments, or dedicated government funding to secure long-term maintenance sustainability. Finally, recognizing that maintenance costs and benefits fluctuate over time, periodic evaluations are necessary to adapt maintenance strategies to evolving budgetary policies and technical bridge conditions, thereby enhancing overall system resilience and cost-effectiveness.

Compared with international best practices UK (Hamer et al., 2022): Lifecycle cost modeling demonstrates long-term savings and efficient budget allocation. Indonesia shows similar financial viability but lacks systematic lifecycle planning. China (Lu & Cai, 2020): Integrated maintenance with IoT and AI enhances efficiency. Indonesia lags in adopting predictive technologies due to regulatory and budgetary constraints. Japan: Risk-based asset management is institutionalized, reducing accident risk and optimizing maintenance cycles. In contrast, Indonesian regulations remain reactive. This contrast highlights that Indonesia's barrier is not financial feasibility, but the absence of regulatory adaptation and advanced monitoring systems.

Railway bridge maintenance is financially feasible because the benefits generated outweigh the costs (*positive NPV* in various discount levels). To be more optimal, the strategy

should focus on preventive maintenance, the use of technology, and sustainable financing schemes involving various stakeholders.

With limited government budgets, bridge maintenance must still be carried out with an efficient and priority-based strategy. Here are the steps that can be implemented to optimize your budget:

1. Risk-Based Maintenance *Prioritization*
    a. Identify bridges with the highest risk of failure based on age, structural conditions, and traffic volume.
    b. Use an asset management approach to map maintenance needs gradually, so that the budget is focused on the bridges that need the most urgent maintenance.
    c. Apply *the Value Engineering* (VE) method to find more cost-effective treatment solutions without compromising quality.
    d. Eliminating the cost of inspecting the bridge, this work is included in the maintenance activities.
2. Implementing Predictive Monitoring and Maintenance Technology
    a. Use IoT sensors and artificial intelligence (AI-based predictive maintenance) to detect potential damage early, so repairs are made before major failures occur.
    b. The use of drones and LiDAR-based inspections can reduce the cost of manual surveys and improve accuracy in monitoring bridge conditions.
3. Alternative Financing Schemes (Outside the State Budget/Regional Budget)
    a. Engage private investors to fund maintenance with a profit-sharing scheme from rail transportation revenues.
    b. The government can sell or transfer the operational rights of other assets that already generate revenue to fund bridge maintenance.
    c. Implement a levy policy or maintenance fund from railway operators to finance infrastructure maintenance.
4. Operational and Material Efficiency
    a. Use more durable and environmentally friendly treatment materials to reduce the frequency of long-term maintenance.
    b. Optimize prefabricated component replacement methods to reduce field repair time and reduce labor costs.
5. Collaboration with Academics and Innovative Research
    c. Work with universities and research institutions to develop cheaper and more efficient treatment technologies

d. Encourage innovation in bridge strengthening techniques with new methods that are more cost-effective.

4. CONCLUSION

This study confirms the hypothesis that railway bridge maintenance in Indonesia remains financially viable under risk-based prioritization, technology-driven inspection, and alternative financing schemes. The cost-benefit analysis shows that the Net Present Value (NPV) remains positive across all discount rate scenarios, demonstrating the financial feasibility and long-term sustainability of such investments. Beyond financial viability, the study highlights that gaps in policy implementation and technical regulations are the main obstacles to effective maintenance.

Academically, this research advances the literature by integrating policy analysis with cost-benefit evaluation an approach not previously applied to Indonesia's railway bridges. Practically, it contributes actionable strategies such as risk-based prioritization of high-risk assets, predictive monitoring using IoT, AI, and drones, the use of prefabricated components, and public–private partnership financing mechanisms. These recommendations not only support the safety and resilience of Indonesia's railway infrastructure but also provide a replicable model for other emerging economies balancing fiscal constraints with safety-critical infrastructure.

Nevertheless, this study has limitations, particularly the reliance on projected cost data and its geographic focus on Jakarta and West Java, which may not fully capture nationwide variations. Future research should broaden the empirical base by incorporating real-time maintenance data, extending the analysis to rural and inter-island bridges, and comparing Indonesia's case with other developing countries. Such efforts will enhance the robustness of performance-based maintenance policies while ensuring both financial efficiency and infrastructure safety.

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Subject: Optimization of Railway Bridge Maintenance Needs Through Performance-Based Policy Evaluation

HASIL PENELAAHAN

Semua catatan reviewer A dan B telah direspons secara substantif dan disertai peningkatan kualitas akademik yang jelas.

Metodologi kini transparan, terstruktur, dan dapat direplikasi.

Diskusi kini mengandung perbandingan lintas negara dan teori manajemen aset.

Referensi sudah memenuhi standar jurnal bereputasi.

DITERIMA – ACCEPTED AFTER MINOR EDITORIAL ADJUSTMENT

EDITORIAL ADJUSTMENT

1. **Pada Pendahuluan :** Tabel 1 List of relevant previous research, Research Gap à **buat dalam paragraph jangan poin-poin**
2. **Pada METHODOLOGY:** Cost-Benefit Analysis (CBA) **à buat dalam paragraph jangan poin-poin**
3. **Result and Discuss :** Recommendations based on *Cost and Benefit Analysis* for Railway Bridge Maintenance, Compared with international best practices, hingga ke bawah **à buat dalam paragraph jangan poin-poin**

Dengan ini kami sampaikan bahwa naskah anda "**diterima**" dengan catatan minor diatas, mohon perbaikan di kirim kembali **1 november 2025.**

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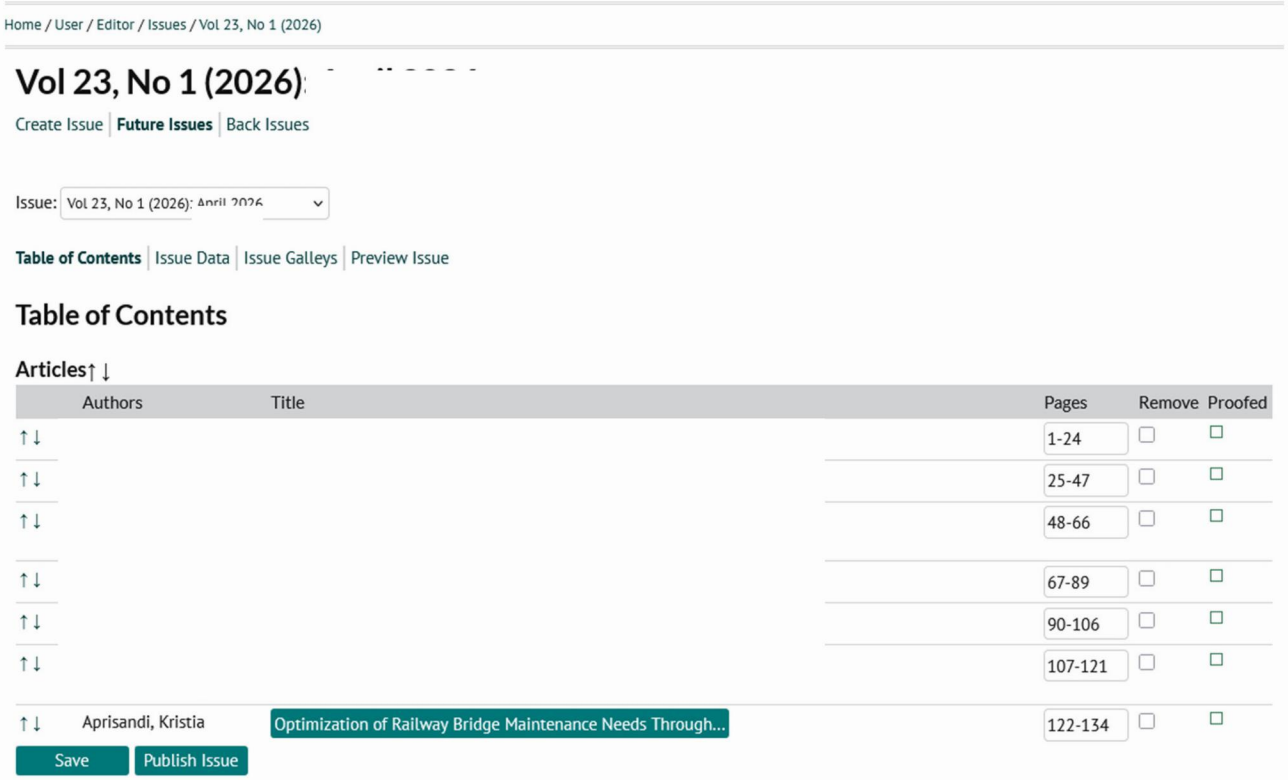

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