Open Science and Technology
Vol. 04 No. 02, 2024 (76-85)
ISSN (Print) :2776-169X
ISSN (Online) :2776-1681

The Influence of Bridge Maintenance Strategies to Extend Service Life in Civil Engineering: A Meta-Analysis Study

Pengaruh Strategi Pemeliharaan Jembatan dalam Memperpanjang Masa Layanan pada Teknik Sipil: Studi Meta-Analisis

Aris Krisdiyanto[1*], Kemmala Dewi[2], Tomi Apra Santosa[3]

[1,2]Universitas 17 Agustus 1945 Semarang, Indonesia
[3] Akademi Teknik Adikarya, Indonesia

*Corresponding email: ariskrisdiyanto123@gmail.com

Submitted:30 November 2024 Accepted: 29 December 2024 Published: 30 December 2024

ABSTRAK

Pemeliharaan jembatan merupakan elemen krusial dalam manajemen infrastruktur teknik sipil untuk memastikan keberlanjutan fungsi struktural dan keselamatan pengguna. Penelitian ini bertujuan untuk menganalisis secara meta-analitis pengaruh berbagai strategi pemeliharaan jembatan terhadap perpanjangan umur layanannya. Data diambil dari 15 studi yang mencakup strategi pemeliharaan preventif, prediktif, korektif, hingga rehabilitasi penuh, serta penggunaannya pada jembatan dengan beragam kondisi lingkungan dan material. Hasil meta-analisis menunjukkan bahwa strategi pemeliharaan jembatan memiliki pengaruh signifikan terhadap perpanjangan umur layanannya dengan nilai (d= 0.825 ; p < 0.001) kategori effect size yang tinggi. Temuan ini memberikan informasi penting dalam pemeliharaan jembatan dalam teknik sipil.

Kata kunci: Infrastruktur Teknik Sipil, Pemeliharaan Jembatan, Umur Layanan; Strategi Pemeliharaan.

ABSTRACT

Bridge maintenance is a crucial element in civil engineering infrastructure management to ensure the sustainability of structural functions and user safety. This study aims to conduct a meta-analytical analysis of the impact of various bridge maintenance strategies on extending their service life. Data were collected from 15 studies covering preventive, predictive, corrective maintenance strategies, and full rehabilitation, as well as their application to bridges with diverse environmental conditions and materials. The results of the meta-analysis indicate that bridge maintenance strategies have a significant impact on extending their service life, with a high effect size (d = 0.825; p < 0.001). These findings provide important insights into bridge maintenance in civil engineering.

Keywords: *Civil Engineering Infrastructure, Bridge Maintenance, Service Life, Maintenance Strategies.*

INTRODUCTION

Bridge infrastructure has a strategic role in supporting mobility and encouraging economic growth in a region (Consoli *et al.*, 2013; Han *et al.*, 2021). As a link between different regions, bridges allow for the movement of goods, services, and people more quickly and efficiently, thereby improving connectivity between regions (Mansour *et al.*, 2019). This infrastructure is the backbone of the transportation system, especially in areas separated by natural obstacles such as rivers, valleys, or mountain passes. With the existence of reliable bridges, accessibility to economic centers, education, and public services can be improved, which ultimately affects the improvement of people's quality of life (Liao *et al.*, 2024). In the context of trade, bridges play an important role in reducing logistics costs and speeding up distribution, thereby increasing the economic competitiveness of a region (Gervásio *et al.*, 2015).

In addition, a well-maintained bridge has a significant impact on economic stability in the long term. Inadequate or damaged infrastructure can result in disruption of mobility, decreased productivity, and increased risk of accidents(Biondini & Frangopol, 2016). This directly affects economic activity and causes great financial losses for the government and society. Therefore, investment in the construction and maintenance of bridges not only supports smooth transportation, but also becomes a key element in creating inclusive and sustainable economic growth (Fernandes *et al.*, 2022). Strong and functional bridges make a significant contribution in ensuring the sustainability of inter-regional relations, strengthening logistics networks, and economic resilience of a country in the midst of evolving global dynamics (Fiore *et al.*, 2020).

Bridge maintenance faces a variety of complex challenges, one of which is the age of the structure. Many bridges that were designed and built decades ago are now beginning to show signs of deterioration due to material fatigue, corrosion, and structural deformation (Liu *et al.*, 2020). This challenge is exacerbated by the use of materials that at the time of construction have not been fully adapted to long-term needs, especially in the face of dynamic loads and extreme environmental conditions. Over time, without adequate maintenance (Brito & Branco, 1998), the capacity of the bridge structure will continue to decline, increasing the risk of failures that can threaten user safety and disrupt transportation networks (Nielsen *et al.*, 2013).

In addition to age, traffic load and environmental conditions are also the main challenges in bridge maintenance. The ever-increasing volume of traffic, including overloaded heavy vehicles, puts additional pressure on the bridge structure which can accelerate the damage process (Almomani & Almutairi, 2020). On the other hand, environmental conditions such as extreme temperature changes, exposure to ultraviolet rays, high humidity, and the presence of corrosive substances such as salt in coastal areas or snowy areas, further accelerate the degradation of materials (Mansour *et al.*, 2019). This combination of excessive traffic loads and environmental factors creates an urgent need for effective, cutting-edge technology-based maintenance strategies, such as the use of sensors for structural health monitoring (SHM) and innovative materials such as high-performance concrete or corrosion-resistant polymers. These efforts are needed to ensure the sustainability of the bridge's function in the long term and prevent potential economic losses resulting from structural failures (Consoli *et al.*, 2013).

Challenges faced in bridge maintenance, such as structural age, traffic load, and environmental conditions, highlight the importance of implementing appropriate maintenance strategies to maintain functional sustainability and extend the service life of bridges (Long *et al.*, 2022). Without a deep understanding of the effectiveness of various maintenance strategies, decisions are at risk of becoming less efficient, potentially increasing costs and increasing the risk of structural failure (Yang *et al.*, 2006). Maintenance strategies, whether preventive, predictive or corrective, should be based on a comprehensive analysis of the actual condition of the bridge and consider external factors that affect the rate of its degradation (Yang *et al.*, 2004).

A deep understanding of the effectiveness of maintenance strategies is also needed to optimize resource allocation, especially in the context of infrastructure budget constraints (Almomani & Almutairi, 2020). Through evidence-based approaches, such as meta-analyses from various studies, it is possible to identify maintenance strategies that best suit the characteristics of the bridge and its surrounding environment (Fiore *et al.*, 2020). For example, preventive maintenance that includes regular inspections and resurfacing of anti-corrosion materials may be more effective for bridges in coastal areas, while structural health monitoring (SHM) technology may be a solution for bridges with high traffic loads (Liu *et al.*, 2020). Thus, understanding the effectiveness of maintenance strategies not only helps to extend the service life of the bridge but also ensures cost efficiency and improves overall user safety (Barone & Frangopol, 2014).

Research by Zhang et al. (2019) shows that regular inspections and preventive maintenance can reduce the rate of structural damage by up to 30% compared to corrective strategies. Another study by Lee et al. (2021) highlights the importance of using structural health monitoring (SHM) technology in identifying early damage, which allows for faster and more effective corrective action. This study indicates that the application of modern technology-based maintenance strategies, such as corrosion or deformation detection sensors, can significantly extend the service life of bridges, especially in infrastructure in areas with extreme environmental conditions. research by Smith *et al.* (2020) stated that preventive maintenance is more effective on concrete bridges than steel bridges, while bridges in coastal areas require special treatment to overcome the effects of corrosion due to high salt levels in the air. In addition, although many individual studies have identified the success of a particular strategy, there is no unified approach to mengevaluasi dan membandingkan berbagai strategi pemeliharaan secara sistematis.

The lack of a comprehensive evaluation of the effectiveness of bridge maintenance strategies in the literature is a fundamental problem that affects decision-making in infrastructure management. Although there is a lot of research on bridge maintenance, the results are often fragmented and do not provide a holistic picture of the most effective strategies for different types of bridges and environmental conditions (Nielsen *et al.*, 2013). This makes it difficult for stakeholders, including civil engineers and policymakers, to determine the best approach to maintain the sustainability of the bridge's function (Stahl *et al.*, 2009). As a result, maintenance is sometimes not optimal, both in terms of cost and results, which has the potential to accelerate structural degradation and increase the risk of malfunction. Based on this is necessary, it allows researchers to integrate the results of various relevant studies, providing a more holistic and comprehensive view of the effectiveness of various maintenance strategies in extending the service life of bridges.

RESEARCH METHODS

The research method used in this study is meta-analysis, which aims to systematically and quantitatively evaluate data from previous studies related to the influence of bridge maintenance strategies in extending the service life of bridges. The data of this meta-analysis research was obtained through google scholar, Sciencedirect and Wiley. The data sources in this study come from 15 articles. The selection of data using the PRISAM 2020 method can be seen in Figure 1. The inclusion criteria in this study are that the research must be relevant, the research is published in 2021-2024; and report complete data to calculate the effect size value. Data analysis with the help of the JASP application.

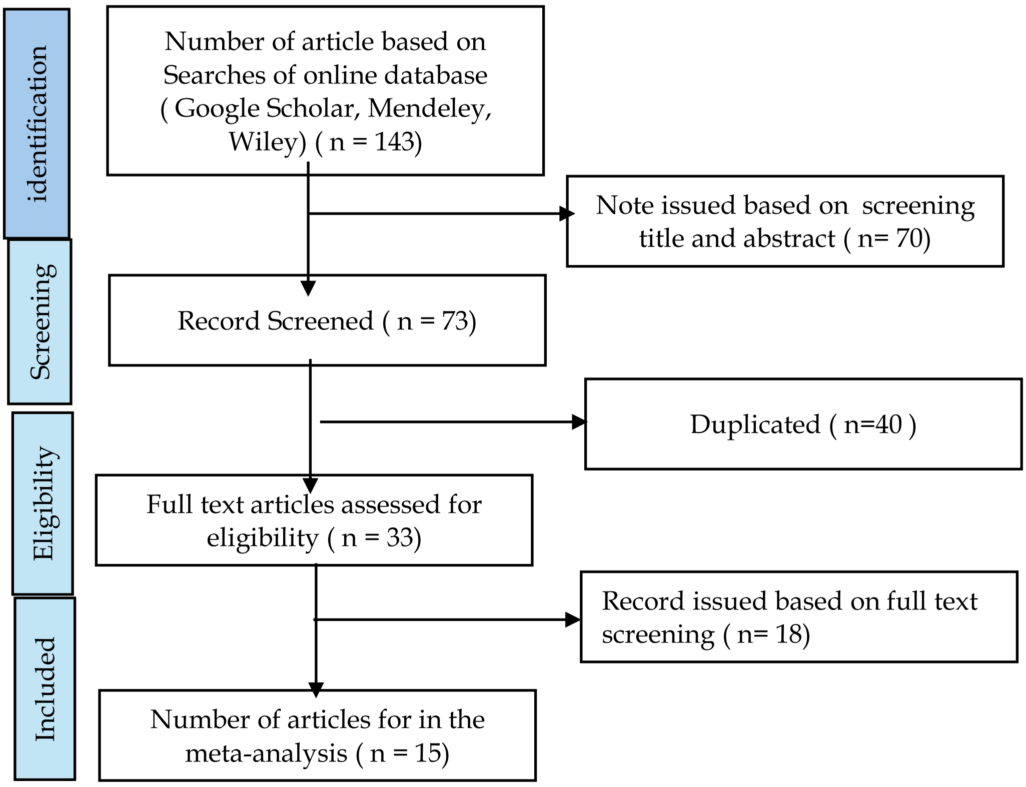

Figure 1. Data Selection Process Through PRISMA (Dewanto *et al.,* 2023;Tamur *et al.,* 2020)

Studies that use irrelevant designs or invalid methodologies will be excluded. Once the appropriate literature has been collected, statistical analysis will be conducted to identify the trends and effectiveness of each bridge maintenance strategy (Borenstein *et al.,* 2007). Techniques such as effect size calculations, heterogeneity analysis, and publication bias test will be used to ensure the accuracy and precision of the findings of this meta-analysis (Asnur *et al.,* 2024; Zulyusri *et al.,* 2023; Tamur *et al.,* 2020). The criteria for the effect size value in this study can be seen in Table 1.

Table 1. Category Effect Size Value

ISSN (Print) :2776-169X
ISSN (Online) :2776-1681

Effect Size	Category
0.0≤ES≤ 0.2	Low
0.2≤ES≤ 0.8	Medium
ES≥ 0.8	High

Source: Borenstein *et al.,* 2007

RESULT AND DISCUSSION

Based on the results of data search through the database, 15 studies met the inclusion criteria. The effect size and error standard can be seen in Table 2.

Table 2. Effect Size and Standard Error Every Research

Code Journal	Years	Effect Size	Standard Error
PN 1	2021	0.93	0.31
PN 2	2023	1.19	0.39
PN 3	2022	0.62	0.19
PN 4	2020	1.34	0.35
PN 5	2025	0.67	0.29
PN 6	2024	0.82	0.27
PN 7	2024	0.44	0.10
PN 8	2023	0.31	0.19
PN 9	2023	1.45	0.40
PN 10	2025	1.09	0.39
PN 11	2024	0.74	0.22
PN 12	2022	0.90	0.45
PN 13	2022	1.12	0.34
PN 14	2024	1.02	0.40
PN 15	2025	0.84	0.34

Based on Table 2, the effect size value of the 15 studies ranged from 0.31 to 1.45. According to Borenstein *et al.,* (2007) of the 15 effect sizes, 5 studies had medium criteria effect sizes and 10 studies had high criteria effect size values. Furthermore, 15 studies were analyzed to determine an estimation model to calculate the mean effect size. The analysis of the fixed and random effect model estimation models can be seen in Table 3.

Table 3. Fixed and Random effect

	Q	df	p
Omnibus test of Coefficients Model	71.798	1	< 0.001
Test of Residual Heterogeneity	23.646	18	< 0.001

Based on Table 3, a Q value of 71.798 was obtained higher than the value of 23.464 with a coefficient interval of 95% and a p value of 0.001 <. The findings can be concluded that the value of 15 effect sizes analyzed is heterogeneously distributed. Therefore, the model used to calculate the mean effect size is a random effect model. Furthermore, checking publication bias through funnel plot analysis and Rosenthal fail safe N (FSN) test (Tamur *et al.*, 2020; Badawi *et al.*, 2022; Ichsan *et al.*, 2023b; Borenstein *et al.*, 2007; Zulkifli *et al.*, 2022). The results of checking publication bias with funnel plot can be seen in Figure 2.

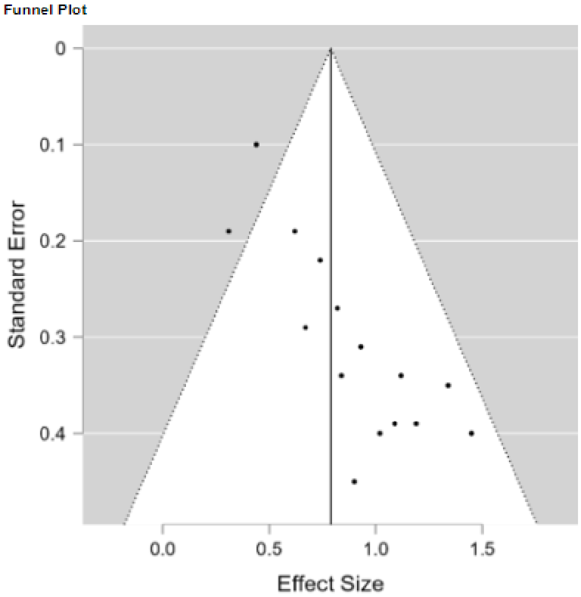

Figure 2. Funnel Plot Standard Error

Based on Figure 2, the analysis of the funnel plot is not yet known whether it is symmetrical or asymmetrical, so it is necessary to conduct a Rosenthal Fail Safe N (FSN) test. The results of the Rosenthal Fail Safe N calculation can be seen in Table 4.

Tabel 4. Fail Safe N

File Drawer Analysis			
	Fail Safe N	Target Significance	Observed Significance
Rosenthal	721	0.050	< 0.001

Based on Table 4, the Fail Safe N value of 721 is greater than the value of 5k + 15 = 5(15) + 10 = 85, so it can be concluded that the analysis of 15 effect sizes in this data is not biased by publication and can be scientifically accounted for. Next, calculate the p-value to test the hypothesis through the random effect model. The results of the summary effect model analysis with the random effect model can be seen in Table 5.

Tabel 5. Mean Effect Size

Coefficient						
	Effect Size	Standard Error	z	p	95 %BCoefficient Interval	
					Lower	Upper
Intercept	0.825	0.193	8.479	< 0.01	0.606	1.211

Based on Table 5, the results of the analysis with the random effect model obtained a lower limit value of 0.606 and an upper limit of 1.211 and a mean effect size value of

0.825 The effect size category in this study is included in the high category. Furthermore, the results of the Z test to determine the significance were obtained 8.473 and the p value < 0.01, so it can be concluded that the application Bridge maintenance strategies have a significant influence on the extension of their service life compared to reactive or corrective maintenance strategies (Alex, 2009). The studies analyzed showed that bridges that were regularly inspected and maintained had lower levels of damage and were more resistant to external factors such as corrosion or excessive traffic loads. This is in line with findings that show that prevention is more effective and more economical than major repairs made after major damage has occurred (Wittocx *et al.,* 2022).

However, while preventive strategies have proven effective, their implementation is often constrained by budget and resource constraints. Many studies show that, while these strategies offer long-term benefits, the initial costs required for routine inspections and more intensive preventive care can be a bottleneck, especially in developing countries or in regions with limited budgets (Almomani & Almutairi, 2020). Therefore, there is a need for the development of more efficient methods in carrying out preventive maintenance, such as the use of new technologies in bridge health monitoring that are more cost-effective, such that can identify damage early without huge costs (Liu *et al.,* 2020). Predictive maintenance strategies, which involve monitoring the condition of bridges using advanced technologies such as sensors or data-driven models to predict damage, also show great potential in extending the service life of bridges. While not as popular as preventive maintenance (Li *et al.,* 2022), research shows that this technology can improve the accuracy of damage detection and minimize the costs associated with manual inspections. However, the adoption of this technology is still limited by installation costs and lack of technical skills in many regions. In addition, most research on predictive maintenance is still limited to the use of specific data and technologies, so more research is still needed to evaluate the effectiveness of these strategies in various contexts (Balogun, 2018; Alex, 2009).

On the other hand, research has aso shown that corrective maintenance strategies, which involve repairing or replacing damaged parts after damage has occurred, have a lower effectiveness in extending the service life of bridges (Yang *et al.,* 2004). While it can address greater damage, corrective maintenance often comes at a higher cost and can cause disruptions in bridge service during the repair process. Therefore, although corrective maintenance cannot be completely avoided, this study underscores the importance of reducing reliance on this approach by improving preventive and predictive maintenance (Long *et al.,* 2022).

The results of this analysis show that an integrated approach, which combines preventive, predictive and corrective maintenance strategies, provides the best results in extending the service life of the bridge (Cables & Wang, 2022). By combining these three approaches, civil engineers can optimize bridge maintenance management, minimize costs, and extend the service life of infrastructure (Fiore *et al.,* 2020). Therefore, it is important to develop evidence-based guidelines that direct stakeholders to select and implement appropriate maintenance strategies according to the specific conditions of each bridge. This research provides important insights in formulating more effective, efficient, and sustainable bridge maintenance policies in the context of broader civil infrastructure development.

CONCLUSION

From the results of this meta-analysis, it can be concluded that the bridge maintenance strategy has a significant influence on the extension of its service life with a high value (d= 0.825; $p < 0.001$) in the high effect size category. These findings provide important information in bridge maintenance in civil engineering. In addition, this study provides evidence-based insights related to the importance of choosing the right maintenance strategy in supporting the extension of bridge service life. This result is expected to be a guide for civil engineering practitioners and policymakers in managing sustainable, efficient, and economical infrastructure.

REFERENCES

Alex. (2009). *Parametric Model for Assessing Factors that Influence Highway Bridge Service Life*.

Almomani, H., & Almutairi, O. N. (2020). Life-cycle maintenance management strategies for bridges in kuwait. *Journal of Environmental Treatment Techniques*, *8*(4), 1556–1562. https://doi.org/10.47277/JETT/8(4)1562

Asnur, L., Jalinus, N., Faridah, A., Apra, T., Ambiyar, R. D., & Utami, F. (2024). *Video-blogs (Vlogs) -based Project : A Meta Analysis*. *14*(5), 1553–1557.

Badawi et al. (2023). Integration of Blended Learning and Project-Based Learning (BPjBL) on Achievement of Students' learning goals: A Meta-analysis study. *Pegem Journal of Education and Instruction*, *13*(4). https://doi.org/10.47750/pegegog.13.04.32

Balogun, T. B. (2018). Integrating Bridge Maintenance Life Cycle Assessments into Bridge Design for Improved Sustainable Decision Making. *Ph D UK*, 247.

Barone, G., & Frangopol, D. M. (2014). Reliability, risk and lifetime distributions as performance indicators for life-cycle maintenance of deteriorating structures. *Reliability Engineering and System Safety*, *123*, 21–37. https://doi.org/10.1016/j.ress.2013.09.013

Biondini, F., & Frangopol, D. M. (2016). Life-Cycle Performance of Deteriorating Structural Systems under Uncertainty: Review. *Journal of Structural Engineering*, *142*(9), 1–17. https://doi.org/10.1061/(asce)st.1943-541x.0001544

Borenstein, M., Hedges, L., & Rothstein, H. (2007). *Introduction to Meta-Analysis*. www.Meta-Analysis.com

Brito, J. de, & Branco, F. A. (1998). Concrete Bridge Management: From Design to Maintenance. *Practice Periodical on Structural Design and Construction*, *3*(2), 68–75. https://doi.org/10.1061/(asce)1084-0680(1998)3:2(68)

Cables, T. B., & Wang, D. (2022). *SS symmetry Numerical Modeling of Ice Accumulation on Natural Wind Conditions*.

Consoli, N. C., Rosa, A. D., & Saldanha, R. B. (2013). Crack-Healing Investigation in Bituminous Materials. *Journal of Materials in Civil Engineering*, *25*(7), 864–870. https://doi.org/10.1061/(ASCE)MT.1943-5533

Dewanto, D., Wantu, H. M., Dwihapsari, Y., Santosa, T. A., & Agustina, I. (2023). Effectiveness of The Internet of Things (IoT)-Based Jigsaw Learning Model on Students' Creative Thinking Skills: A- Meta-Analysis. *Jurnal Penelitian Pendidikan IPA*, *9*(10), 912–920. https://doi.org/10.29303/jppipa.v9i10.4964

Fernandes, J. N. D., Matos, J. C., Sousa, H. S., & Coelho, M. R. F. (2022). Life Cycle

Analysis of a Steel Railway Bridge over the Operational Period considering Different Maintenance Scenarios: Application to a Case Study. *Advances in Civil Engineering*, *2022*. https://doi.org/10.1155/2022/3010001

Fiore, A., Liuzzi, M. A., & Greco, R. (2020). Some shape, durability and structural strategies at the conceptual design stage to improve the service life of a timber bridge for pedestrians. *Applied Sciences (Switzerland)*, *10*(6). https://doi.org/10.3390/app10062023

Gervásio, H., da Silva, L. S., Perdigão, V., Orcesi, A., & Andersen, R. (2015). Influence of Maintenance Strategies on the Life Cycle Performance of Composite Highway Bridges. *Structural Engineering International*, *25*(2), 184–196. https://doi.org/10.2749/101686614X14043795569978

Han, X., Yang, D. Y., & Frangopol, D. M. (2021). Optimum maintenance of deteriorated steel bridges using corrosion resistant steel based on system reliability and life-cycle cost. *Engineering Structures*, *243*. https://doi.org/10.1016/j.engstruct.2021.112633

Ichsan, I., Suharyat, Y., Santosa, T. A., & Satria, E. (2023). Effectiveness of STEM-Based Learning in Teaching 21 st Century Skills in Generation Z Student in Science Learning: A Meta-Analysis. *Jurnal Penelitian Pendidikan IPA*, *9*(1), 150–166. https://doi.org/10.29303/jppipa.v9i1.2517

Li, L., Lu, Y., & Peng, M. (2022). Deterioration Model for Reinforced Concrete Bridge Girders Based on Survival Analysis. *Mathematics*, *10*(23). https://doi.org/10.3390/math10234436

Liao, S., Peng, J., Wang, L., & Zhang, J. (2024). Optimization of maintenance program for bridge cable in service lifetime. *Bridge Maintenance, Safety, Management, Digitalization and Sustainability - Proceedings of the 12th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2024*, 2791–2796. https://doi.org/10.1201/9781003483755-331

Liu, S. S., Huang, H. Y., & Kumala, N. R. D. (2020). Two-stage optimization model for life cycle maintenance scheduling of bridge infrastructure. *Applied Sciences (Switzerland)*, *10*(24), 1–26. https://doi.org/10.3390/app10248887

Long, L., Alcover, I. F., & Thöns, S. (2022). Utility analysis for SHM durations and service life extension of welds on steel bridge deck. *Structure and Infrastructure Engineering*, *18*(4), 492–504. https://doi.org/10.1080/15732479.2020.1866026

Mansour, D. M. M, Moustafa, I. M., Khalil, A. H., & Mahdi, H. A. (2019). An assessment model for identifying maintenance priorities strategy for bridges. *Ain Shams Engineering Journal*, *10*(4), 695–704. https://doi.org/10.1016/j.asej.2019.06.003

Nielsen, D., Raman, D., & Chattopadhyay, G. (2013). Life cycle management for railway bridge assets. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *227*(5), 570–581. https://doi.org/10.1177/0954409713501297

Stahl, D., Delong, E., Wagner, M., Jetten, M., & Ramos, J. L. (2009). *r P Fo ee r R ev ie w On r P Fo ie w*. *2017*(1), 1–5.

Tamur, M., Juandi, D., & Kusumah, Y. S. (2020). The effectiveness of the application of mathematical software in indonesia; a meta-analysis study. *International Journal of Instruction*, *13*(4), 867–884. https://doi.org/10.29333/iji.2020.13453a

Wittocx, L., Buyle, M., Audenaert, A., Seuntjens, O., Renne, N., & Craeye, B. (2022). Revamping corrosion damaged reinforced concrete balconies: Life cycle assessment and life cycle cost of life-extending repair methods. *Journal of Building*

Engineering, *52*. https://doi.org/10.1016/j.jobe.2022.104436

Yang, S. I., Frangopol, D. M., Kawakami, Y., & Neves, L. C. (2006). The use of lifetime functions in the optimization of interventions on existing bridges considering maintenance and failure costs. *Reliability Engineering and System Safety*, *91*(6), 698–705. https://doi.org/10.1016/j.ress.2005.06.001

Yang, S. I., Frangopol, D. M., & Neves, L. C. (2004). Service life prediction of structural systems using lifetime functions with emphasis on bridges. *Reliability Engineering and System Safety*, *86*(1), 39–51. https://doi.org/10.1016/j.ress.2003.12.009

Youna Chatrine Bachtiar, Mohammad Edy Nurtamam, Tomi Apra Santosa, Unan Yasmaniar Oktiawati, & Abdul Rahman. (2023). the Effect of Problem Based Learning Model Based on React Approach on Students' 21St Century Skills: Meta-Analysis. *International Journal of Educational Review, Law And Social Sciences (IJERLAS)*, *3*(5), 1576–1589. https://doi.org/10.54443/ijerlas.v3i5.1047

Zulkifli, Z., Satria, E., Supriyadi, A., & Santosa, T. A. (2022). Meta-analysis: The effectiveness of the integrated STEM technology pedagogical content knowledge learning model on the 21st century skills of high school students in the science department. *Psychology, Evaluation, and Technology in Educational Research*, *5*(1), 32–42. https://doi.org/10.33292/petier.v5i1.144

Zulyusri, Z., Santosa, T. A., Festiyed, F., Yerimadesi, Y., Yohandri, Y., Razak, A., & Sofianora, A. (2023). Effectiveness of STEM Learning Based on Design Thinking in Improving Critical Thinking Skills in Science Learning: A Meta-Analysis. *Jurnal Penelitian Pendidikan IPA*, *9*(6), 112–119. https://doi.org/10.29303/jppipa.v9i6.3709