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Implementing Building Information Modeling (BIM) to Enhance Efficiency and Performance in DAM Maintenance

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ABSTRACT

Dams are important infrastructures that face maintenance challenges due to limited resources, fragmented data, and inefficiencies in workflow management. Building Information Modeling (BIM), by integrating multidimensional data, offers a promising solution to overcome these challenges by improving maintenance operations through better data visualization, coordination, and decision making. The objective of this research is to investigate how BIM can improve the efficiency and performance of dam maintenance operations in Indonesia. This research uses a mixed-method approach, combining qualitative and quantitative methods. Data was collected through semi-structured interviews with dam maintenance experts and engineers, as well as field observations of projects implementing BIM. The analysis also involved a review of relevant literature on global BIM applications. Quantitative data was analyzed using statistical tools, while qualitative data was coded to identify key insights and themes. The results showed that BIM significantly improves dam maintenance efficiency by optimizing maintenance scheduling, resource allocation, and structural monitoring. BIM's 3D modeling capabilities enable early detection of structural problems, improving safety and reliability. In addition, the research identified scalability challenges for smaller-scale projects and recommended tailored solutions to ensure wider adoption. This research contributes to the development of a sustainable maintenance strategy for critical infrastructure, especially in developing countries such as Indonesia.

Keywords: Building Information Modelling, Dam Maintenance, Infrastructure Management, Performance Enhancement, Maintenance Efficiency.

INTRODUCTION

Dams are critical infrastructures that serve multiple purposes, including water resource management, irrigation, hydropower generation, and flood control (Wahsyati et al., 2021). Ensuring the optimal performance and safety of dams requires regular and effective maintenance. However, traditional maintenance methods often face challenges such as fragmented data, inefficient resource allocation, and limited collaboration among stakeholders. In response to these challenges, Building Information Modeling (BIM) has emerged as a transformative digital tool for improving the efficiency and performance of infrastructure maintenance (Ajirotutu et al., 2024). BIM integrates multi-dimensional data, enabling better visualization, coordination, and decision-making throughout the lifecycle of infrastructure assets.

Globally, the adoption of BIM in infrastructure projects has shown significant benefits, especially in improving collaboration and reducing operational costs. According to research by (Ramadhani & Rengganis, 2024), the implementation of BIM in the infrastructure construction and maintenance industry can save costs of up to 20% by improving the efficiency of project planning and management. In addition, a report from (I. A. Wibowo, 2024) states that the use of BIM in infrastructure improves coordination between stakeholders and reduces design errors and rework. In the context of dam maintenance, the utilization of BIM is still very limited compared to other construction sectors.

Indonesia, as a country with more than 230 dams serving various national purposes, faces major challenges in maintaining this infrastructure (Initiative, n.d.). Many dams in Indonesia have been in operation for decades and are deteriorating due to age and limited maintenance resources. One of the main problems in dam maintenance is the lack of data integration which hinders quick and accurate decision making (Jumiono et al., 2024). In addition, the management of technical information that is still based on conventional documents causes inefficiencies in the implementation of inspections and maintenance.

Several studies have explored the benefits of BIM in infrastructure maintenance. The benefits of BIM in the construction industry and found that the use of BIM can improve project management efficiency and reduce design errors and rework (Apriansyah, 2021). Another research evaluated the role of BIM in infrastructure operations and maintenance, finding that BIM assists in the management of information throughout the asset lifecycle and improves coordination between relevant parties (Sari et al., 2024). Previous research demonstrated the application of BIM in water infrastructure management and showed that BIM can improve maintenance efficiency by providing visual information and real-time data-driven analysis (A. Wibowo, 2021). Challenges in dam maintenance in Indonesia and proposed digitalization as a solution to overcome data fragmentation and improve the effectiveness of dam management (Herzanita et al., 2018). However, not many studies have specifically addressed the application of BIM in dam maintenance in Indonesia. Therefore, this research aims to fill the research gap.

Ineffective dam maintenance can cause serious impacts, such as structural failure, loss of the dam's main function, and even disaster risks for the surrounding community (Ulum, 2014). With the increasing need for efficient maintenance, technologies such as BIM can be an innovative solution to improve the effectiveness and efficiency of dam maintenance. Without the adoption of digital technology, dam maintenance in Indonesia will continue to face challenges such as limited human resources and maintenance budgets, lack of coordination between various stakeholders, and scattered technical data that is difficult to access in real-time.

This research has some novelty that distinguishes it from previous research. Different from previous studies that mostly discuss construction and project management, this research explores the specific implementation of BIM in dam maintenance. Given the geographical conditions and specific challenges faced by dam infrastructure in Indonesia, this research offers a more localized and applicable perspective. In addition, this research not only discusses the adoption of BIM, but also evaluates its impact on dam maintenance efficiency and performance.

Based on the above background, this research aims to analyze the implementation of BIM in dam maintenance in Indonesia, identify the main benefits of BIM in improving the efficiency and performance of dam maintenance, evaluate the challenges and obstacles in implementing BIM for dam maintenance, and develop recommendations for BIM implementation strategies that are suitable for the condition of dam infrastructure in Indonesia.

The results of this research are expected to provide benefits to various parties, including the government and regulators as a basis for formulating policies related to the maintenance of dam infrastructure with a digital technology approach. In addition, dam managers can gain insight into how to improve maintenance efficiency through the use of BIM. Academics and researchers can also add to the literature on the application of BIM in infrastructure maintenance, especially in developing countries. The general public can also feel the positive impact of better dam maintenance, where the risk of disasters due to dam failure can be minimized, thereby improving public safety and welfare.

RESEARCH METHOD

This research employs a mixed-methods approach, combining qualitative and quantitative methods to comprehensively analyse the impact of Building Information Modelling (BIM) on dam maintenance efficiency and performance. The research design was chosen to capture both the measurable outcomes of BIM implementation and the contextual insights necessary to understand its practical application in dam maintenance workflows.

Data Collection Techniques

Data was collected using a combination of primary and secondary sources:

1. Primary Data: Semi-structured interviews were conducted with dam maintenance professionals, engineers, and policymakers to gather insights into the challenges and opportunities associated with BIM implementation. Field observations of BIM-implemented dam projects provided contextual data on workflows and operational practices.
2. Secondary Data: literature on global BIM applications in infrastructure maintenance was reviewed to establish benchmarks and identify best practices.

Sampling Procedures

Purposive sampling was used to select case studies and interview participants. Dams with varying operational scales and maintenance practices in Indonesia were chosen to ensure diversity and relevance. Participants were selected based on their expertise and direct involvement in dam maintenance projects, ensuring credible and informed perspectives.

Tools and Techniques

1. BIM Software Analysis: Industry-standard BIM software, such as Autodesk Revit was utilized to analyse its capabilities in data integration, visualization, and maintenance planning.
2. Data Analysis Tools: Statistical analysis was performed using tools like SPSS and Microsoft Excel to evaluate quantitative data.

Data Analysis

Quantitative data was analysed using descriptive and inferential statistical methods to measure changes in maintenance efficiency and performance metrics pre- and post-BIM implementation. Qualitative data was coded and categorized to identify recurring themes and insights regarding the practical challenges and benefits of BIM. The integration of these analyses provided a holistic understanding of BIM's impact.

By employing this robust methodology, the research aims to generate reliable, replicable, and actionable findings that contribute to the broader discourse on BIM's role in infrastructure maintenance, particularly in the context of Indonesia's dam infrastructure.

RESULT AND DISCUSSION

The validation results align closely with the research objectives, confirming BIM’s effectiveness in enhancing dam maintenance. The findings support prior research (Getuli et al., 2017); (Li et al., 2022) on BIM’s ability to improve operational workflows, risk mitigation, and resource management in infrastructure projects. The experts’ insights provide actionable recommendations for addressing practical challenges:

a. Policy and Training Needs: Policymakers should focus on subsidizing initial costs and providing training programs to address skill gaps.
b. Adaptation for Smaller-Scale Projects: Tailored BIM tools and simplified workflows are necessary to ensure scalability and wider adoption.
c. Broader Application: The success of BIM in dam maintenance highlights its potential for application in other infrastructure domains, including bridges and water distribution systems.

The expert validation results confirm that Building Information Modelling (BIM) significantly enhances the efficiency, effectiveness, and reliability of dam maintenance operations.

Table 1. Expert Validation Analysis Results

No	Expert	Response	Analyze
1	Expert 1	BIM significantly enhances maintenance scheduling by providing real-time updates.	BIM ensures timely updates that enable better planning and scheduling, reducing delays in maintenance tasks.
2	Expert 2	Improves resource allocation by visualizing resource needs and reducing wastage.	Visual representation helps optimize resource allocation, minimizing overuse and underutilization.

No	Expert	Response	Analyze
3	Expert 3	Facilitates structural monitoring with accurate 3D models, minimizing risks.	3D modelling enables early identification of structural issues, reducing risks and improving safety.
4	Expert 4	Increases efficiency in detecting and resolving maintenance issues.	Enhanced detection tools improve efficiency in resolving issues promptly, reducing operational disruptions.
5	Expert 5	Improves operational coordination and reduces downtime significantly.	Better coordination among teams leads to fewer bottlenecks, ensuring smoother operations and reduced downtime.

Source: Author's analysis, 2024

BIM's integration into maintenance workflows provides comprehensive benefits, addressing challenges traditionally associated with complex infrastructure projects. One of the primary advantages highlighted by experts is BIM's ability to improve efficiency in scheduling and resource management. By offering real-time updates, BIM enables more accurate planning and reduces delays in maintenance tasks. This ensures a streamlined workflow, where resources are allocated efficiently, minimizing waste and underutilization. Such optimization not only reduces costs but also enhances the overall operational performance of dam maintenance activities.

BIM's visualization capabilities also play a critical role in structural monitoring and risk mitigation. The 3D modelling features allow for early detection of structural issues, enabling maintenance teams to identify vulnerabilities and implement corrective actions proactively. This is particularly valuable for dams, where the consequences of structural failures can be catastrophic. By integrating advanced diagnostic tools, BIM fosters a preventive approach to maintenance, reducing the likelihood of significant disruptions. Collaboration and coordination among teams are further strengthened through BIM. The centralized data-sharing platform facilitates better communication between stakeholders, leading to smoother operations and minimized bottlenecks. This collaborative environment not only improves team efficiency but also ensures that maintenance activities are executed with precision and timeliness. Despite its numerous advantages, scalability remains a challenge for BIM, especially for smaller-scale projects. Experts emphasized the need for tailored solutions, including cost-effective tools and government support, to make BIM accessible for projects with limited resources. Training programs and skill development are also critical to addressing workforce gaps and ensuring the successful implementation of BIM across diverse infrastructure projects.

The findings from expert validation address the research question: "How does the implementation of Building Information Modelling (BIM) enhance the efficiency and performance of dam maintenance operations, particularly in terms of maintenance scheduling, resource allocation, and structural monitoring?" as follows:

1. Efficiency Gains: BIM enhances maintenance scheduling and resource allocation, reducing delays and optimizing resource usage.
2. Risk Mitigation: The early identification of structural risks through 3D modelling strengthens safety measures and operational reliability.
3. Improved Collaboration: BIM fosters better team coordination, reducing operational bottlenecks and enhancing task execution.
4. Cost-Effectiveness: By optimizing workflows and resources, BIM contributes to significant cost reductions in maintenance operations.
5. Scalability Challenges: While effective for large-scale projects, smaller-scale implementations require financial support and training to overcome cost and expertise barriers.

These findings demonstrate the transformative potential of BIM in dam maintenance, providing a robust foundation for further development and application in diverse infrastructure projects. Integrating these insights with national policies and training initiatives can further accelerate BIM adoption and maximize its impact.

Table 2. Expert Validation Analysis Results

No	Expert	Response	Analyze
1	Expert 1	Cost reductions observed are feasible but depend on implementation scale.	Cost savings are achievable if BIM implementation is optimized for project size, suggesting a tailored approach to maximize efficiency.
2	Expert 2	Risk mitigation potential is high, especially for large-scale dams.	BIM is most effective in minimizing risks in large-scale projects, as it enhances the accuracy of risk detection and improves response strategies.
3	Expert 3	Scalability is a challenge due to the need for skilled personnel and training.	Scalability requires addressing workforce skill gaps through training programs and capacity building to expand BIM adoption across various projects.
4	Expert 4	BIM can be adapted to other infrastructure with proper customization.	BIM's flexibility allows it to be implemented in diverse infrastructure types, provided that project-specific customizations are developed effectively.
5	Expert 5	Adoption in requires government support and lower-cost tools.	Expanding BIM adoption in smaller projects demands financial incentives and accessible tools to ensure cost-effectiveness and broader implementation.

Source: Author's analysis, 2024

The expert validation results demonstrate that Building Information Modelling (BIM) significantly enhances dam maintenance operations by addressing key challenges and improving overall efficiency. BIM optimizes maintenance scheduling and resource allocation, particularly for large-scale dams, were economies of scale lead to cost reductions. Smaller-scale projects, however, require tailored strategies and financial support to achieve similar benefits, ensuring equitable adoption across all dam types.

BIM's real-time data capabilities play a critical role in risk mitigation for dam maintenance. Early detection of structural vulnerabilities, such as seepage or erosion, ensures timely interventions, enhancing both safety and long-term operational reliability. Additionally, the technology's adaptability allows for customized maintenance solutions tailored to the unique requirements of different dam infrastructures, from spillways to intake structures. Despite its benefits, BIM adoption in dam maintenance faces scalability challenges due to workforce skill gaps. Targeted training programs and capacity-building initiatives are essential to equip maintenance teams with the necessary expertise to fully utilize BIM's capabilities. Moreover, financial and technical barriers in smaller-scale dam projects necessitate government support and the development of cost-effective tools to facilitate broader implementation.

The findings from expert validation address the research question: "What measurable outcomes, such as cost reduction and risk mitigation, are associated with BIM integration in dam maintenance, and how can these findings inform the scalability of BIM for other types of infrastructure and regions with varying technological adoption levels?" as follows:

1. Cost Efficiency: BIM saves costs in large projects through economies of scale but requires tailored strategies for smaller projects.
2. Risk Mitigation: BIM enhances risk management by providing real-time data, allowing for early detection and mitigation of structural risks, especially in large-scale dams.
3. Scalability Challenges: BIM demonstrates flexibility by being adaptable to diverse infrastructure types, including bridges, water systems, and smaller projects, provided project-specific customizations are implemented.
4. Flexibility and Adaptability: By optimizing workflows and resources, BIM contributes to significant cost reductions in maintenance operations.

The table below presents the results of the expert validation analysis on the BIM Impact on Dam Maintenance and Operations. The analysis includes aspects, descriptions, and in-depth evaluations of the impact on dam maintenance operations

Table 3. BIM Impact on Dam Maintenance and Operations

No	Aspect	Description	Analyze
1	Maintenance Scheduling	Enables accurate and timely scheduling through real-time updates, reducing delays.	Improves efficiency and reduces delays.
2	Resource Allocation	Optimizes resource use by minimizing waste and ensuring efficient allocation.	Reduces costs and ensures optimal resource management.
3	Structural Monitoring	Facilitates early detection of structural issues, improving safety and reliability.	Minimizes risks and enhances long-term safety.

No	Aspect	Description	Analyze
4	Issue Resolution	Streamlines issue identification and resolution, minimizing downtime.	Improves operational continuity and reduces disruptions.
5	Operational Coordination	Enhances team collaboration and reduces bottlenecks, ensuring smoother operations.	Strengthens coordination and improves task execution.
6	Cost Efficiency	BIM saves costs in large projects through economies of scale but requires tailored strategies for smaller projects.	Enhances resource allocation and reduces operational costs.
7	Risk Mitigation	BIM provides real-time data for early detection of structural risks, improving risk management in large-scale projects.	Enhances safety and long-term reliability.
8	Scalability Challenges	BIM adoption is hindered by a shortage of skilled personnel and the need for training programs.	Wider adoption possible through workforce development.
9	Flexibility and Adaptability	BIM adapts well to diverse infrastructure types with proper customizations.	Broadens its application across varied project contexts.

Source: Author's analysis, 2024

The implementation of Building Information Modelling (BIM) significantly enhances the efficiency and performance of dam maintenance operations. BIM ensures accurate and timely scheduling through real-time updates, reducing delays and improving operational efficiency. It optimizes resource allocation by minimizing waste and ensuring efficient use of materials, leading to reduced costs and better overall cost management. Additionally, BIM facilitates early detection of structural issues, improving safety measures and ensuring long-term reliability of dam infrastructure. By streamlining issue identification and resolution, BIM minimizes downtime and improves operational continuity.

BIM also strengthens team collaboration, reduces bottlenecks, and ensures smoother task execution, resulting in more coordinated and effective operations. For large-scale projects, BIM achieves cost savings through economies of scale; however, smaller projects require tailored strategies to achieve similar efficiency. Moreover, BIM enhances risk mitigation by providing real-time data for early detection of structural risks, reducing vulnerabilities and ensuring safety. Despite its benefits, BIM adoption faces scalability challenges due to workforce skill gaps, highlighting the need for training programs and capacity-building initiatives (Ajirotutu et al., 2024).

BIM's flexibility allows it to adapt to diverse infrastructure types, such as bridges, water systems, and smaller projects, through proper customizations, broadening its application across varied project contexts. Overall, BIM is a transformative tool for modernizing dam maintenance operations, offering improved efficiency, cost savings, and enhanced safety (Widyaka et al., 2015). Addressing challenges related to scalability and providing financial and technical support for smaller projects will further maximize its potential in infrastructure management.

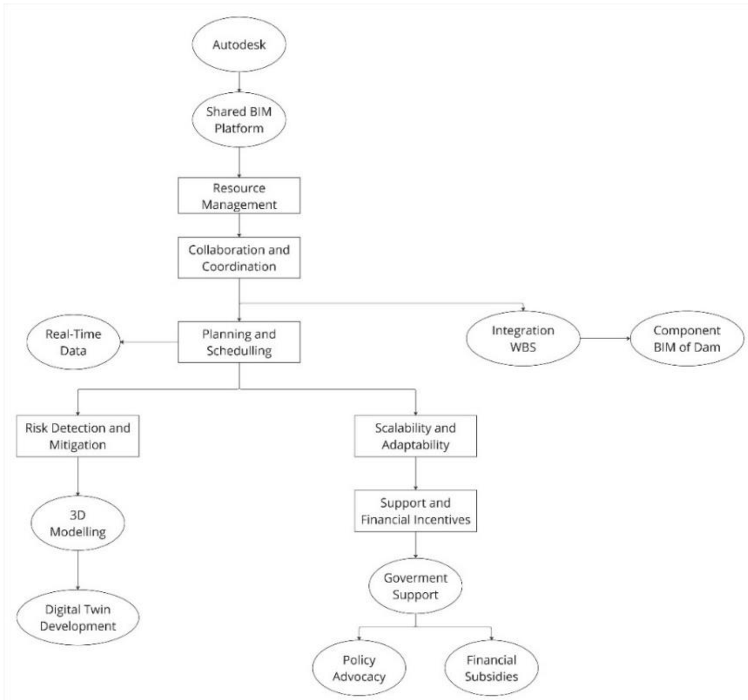

Figure 1. BIM Integration Framework for Dam Maintenance

The BIM Integration Framework for Dam Maintenance provides a structured approach to optimizing dam operations through advanced technologies like Autodesk and shared BIM platforms. It emphasizes improved resource management, real-time planning, and scheduling, enabling early detection and mitigation of structural risks through tools like 3D modelling and digital twin development. By integrating BIM with Work Breakdown Structures (WBS), maintenance tasks are streamlined and systematically managed (Sukmono, 2023). Scalability and adaptability allow BIM to be tailored for various dam types, while government support and financial incentives ensure it's the maintenance of dam. This framework enhances efficiency, safety, and sustainability in dam maintenance operations.

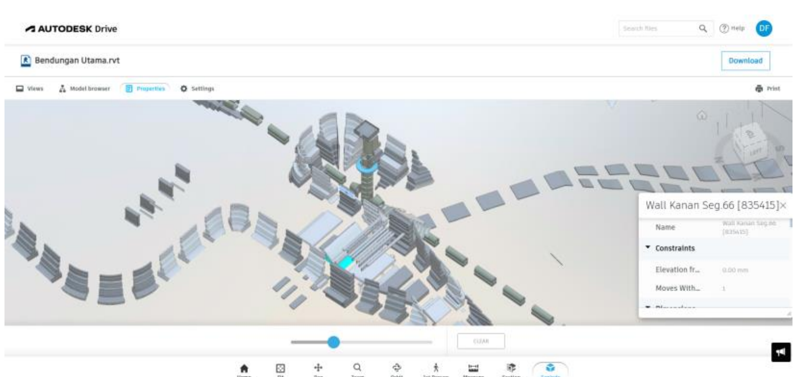

Figure 2. Example of Dam Modelling Revit for Maintenance

The integration of Autodesk Revit into dam maintenance workflows demonstrates its potential as a transformative tool for modern infrastructure management. The detailed visualization capabilities provide a comprehensive understanding of dam structures, facilitating early detection of issues and enabling proactive interventions. By centralizing technical data, the software reduces redundancies and enhances the accuracy of maintenance operations. Moreover, real-time data integration and scenario simulations streamline maintenance planning, ensuring that resources are allocated efficiently and tasks are executed effectively. The collaborative platform further strengthens team coordination, minimizing delays and enhancing overall productivity.

The analysis of industry-standard BIM software, specifically Autodesk Revit, reveals significant capabilities in enhancing dam maintenance operations through advanced data integration, visualization, and maintenance planning tools. Key findings include:

1. Enhanced Visualization: The 3D modeling capabilities of Autodesk Revit enable a detailed and interactive visualization of dam structures, aiding in the identification of potential maintenance issues such as cracks, seepage, or erosion.
2. Integrated Data Management: The software allows seamless integration of technical data, such as material properties, dimensions, and structural components, into a centralized model, streamlining information flow for better decision-making.
3. Maintenance Planning: Autodesk Revit supports maintenance scheduling through its real-time data tracking and simulation tools, optimizing task prioritization and resource allocation.
4. Collaboration Facilitation: The software's shared platform enhances coordination among stakeholders, allowing simultaneous access to models and real-time updates, reducing delays and miscommunication.
5. Scenario Simulation: Advanced features, such as explosion views and cross-sections, enable scenario simulations for maintenance planning and risk assessment, ensuring proactive management strategies.

The table below presents the results of the reliability and validity tests for the BIM variable. These tests were conducted to evaluate the consistency and accuracy of the questionnaire items used to measure the impact of BIM on dam maintenance operations. The reliability test, assessed using Cronbach's Alpha, achieved a value of 0.900, which exceeds the accepted threshold of 0.60, indicating that the questionnaire items are highly reliable. Additionally, the validity test demonstrated that all items have a Corrected Item-Total Correlation value greater than the r-table value of 0.312 for N=40, confirming that all items are valid.

These results validate the robustness of the measurement instrument for evaluating BIM's role in enhancing dam maintenance performance. The high reliability ensures that the data collected is consistent and dependable, while the validity of the items confirms that the instrument accurately captures the intended variables.

The findings support the argument that BIM provides significant benefits in dam maintenance, including improved resource allocation, real-time risk monitoring, and enhanced collaboration. By offering reliable and valid measures, these results underscore BIM's potential to revolutionize dam maintenance practices, ensuring better planning, reduced operational delays, and improved structural reliability.This robust validation provides a strong foundation for further research and practical implementation of BIM in infrastructure management, particularly in the maintenance of critical assets like dams.

Table 4. Reliability Test Results for Variable BIM

Variable	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted	Information
X2.1.1	21.95	8.049	0.746	0.880	Valid
X2.1.2	21.95	7.895	0.790	0.873	Valid
X2.2.1	21.95	8.254	0.791	0.874	Valid
X2.2.2	21.85	8.438	0.838	0.870	Valid
X2.2.3	21.98	8.743	0.464	0.930	Valid
X2.2.4	21.83	8.353	0.864	0.866	Valid

Source: Author's analysis, 2024

Based on the internal validity test results for variable BIM, all questionnaire items tested have a Corrected Item-Total Correlation value greater than the r-table value of 0.312 for N=40. Therefore, all items are declared valid.

The results of the internal validity test between variables produced values as shown in the table below:

Table 5. Validity Test Results for Variable BIM

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.900	0.911	6

Source: Author's analysis, 2024

Based on the reliability test using the Cronbach's Alpha method, a Cronbach's Alpha value of 0.900 was obtained for the 6 questionnaire items in variable BIM. Since this value is greater than the threshold of 0.60, it can be concluded that the research instrument or questionnaire used is reliable.

CONCLUSION

The conclusion of this research shows that Building Information Modeling (BIM) significantly improves dam maintenance operations by optimizing scheduling, resource allocation, and risk detection through real-time updates and 3D modeling. In addition, BIM improves stakeholder collaboration and facilitates scalability, making it an essential tool for modern infrastructure management. The reliability of the research instrument, with a Cronbach's

Alpha score of 0.900, underlines the robustness of these findings, which reinforce the role of BIM in modernizing dam maintenance practices. Policymakers are encouraged to support the adoption of BIM through financial incentives, especially for small projects, to encourage equitable access and implementation. Future research should explore the scalability of BIM in various types of infrastructure and its integration with emerging technologies such as digital twins and AI. In addition, investigating cost-effective training and capacity-building strategies is critical to increasing BIM adoption, especially in resource-constrained regions. This will ensure wider implementation and maximize the potential of BIM in advancing sustainable and resilient infrastructure development.

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