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Optimizing Dam Maintenance: An Integrated BIM-WBS Operational Model

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ABSTRACT

This study addresses the challenges of inefficient dam maintenance by proposing and validating an integrated operational model that leverages Building Information Modeling (BIM) and Work Breakdown Structure (WBS). Traditional dam maintenance often suffers from poor coordination, inadequate resource allocation, and scheduling delays. To overcome these limitations, this research developed a novel model that seamlessly integrates BIM's 3D visualization and data management capabilities with the hierarchical structure of WBS. A mixed-method approach, combining literature review, expert validation, and a case study application, was employed to develop and evaluate the model. The resulting operational model demonstrated improved task efficiency, resource optimization, and stakeholder collaboration through real-time task tracking, streamlined workflows, and enhanced prioritization of maintenance activities. Expert feedback confirmed the model's practicality and effectiveness in resolving common maintenance issues, highlighting its potential to improve communication, reduce delays, and increase the accuracy of maintenance planning. The validated BIM-WBS integrated model provides a robust framework for enhancing dam maintenance performance, offering data-driven decision-making and improved stakeholder collaboration. Future research directions include exploring the model's applicability to other infrastructure types and integrating real-time technologies like IoT and AI for predictive maintenance capabilities.

KEYWORDS

Building Information Modelling (BIM), Work Breakdown Structure (WBS), Dam Maintenance Efficiency

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1. INTRODUCTION

Dams are critical infrastructure assets, playing a vital role in water resource management, irrigation, flood control, and hydroelectric power generation globally, and particularly in Indonesia. Indonesian Regulation of the Minister of Public Works and Housing Number 27 of 2015 defines a dam as a structure designed to retain water, mining waste, or sludge, creating a reservoir. These structures are essential for Indonesia's socio-economic development, providing crucial water resources for domestic, municipal, and industrial use (DMI), and supporting agricultural productivity through irrigation. However, the effective operation and maintenance (O&M) of Indonesia's aging dam infrastructure faces significant challenges, including structural degradation exacerbated by climate variability (Sari et al., 2020), resource constraints (Fernandes Heleno, 2021), and the potential for catastrophic failure due to seismic activity or landslides.

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Reports of deteriorated infrastructure at dams such as Bonelemo (Ali, 2024) and Seu Lepan (Hasibuan, 2024) underscore the urgency of improved O&M strategies.

Current O&M practices in Indonesia are demonstrably inadequate, leading to recurring damage and functional inefficiencies. While previous research has explored the individual applications of Building Information Modelling (BIM) and Work Breakdown Structures (WBS) in infrastructure management, the potential synergistic benefits of integrating these tools for optimized dam maintenance remain largely untapped. This research addresses this critical gap by developing and rigorously validating an integrated BIM-WBS operational model designed to significantly enhance dam maintenance efficiency in Indonesia.

This study addresses three primary research questions: (1) How can BIM and WBS be effectively integrated to optimize dam maintenance processes, leveraging BIM's visualization and data management capabilities with WBS's systematic task organization? (2) What are the operational benefits and challenges of implementing a BIM-WBS integrated framework in real-world dam maintenance scenarios? (3) How does the proposed integrated BIM-WBS model address existing gaps in current dam maintenance strategies and provide innovative solutions?

This research offers a novel contribution by proposing and validating an integrated BIM-WBS framework for dam maintenance, a significant advancement over existing approaches that focus on either BIM or WBS in isolation. The methodology employs a mixed-methods approach e.g., case study analysis, expert interviews, quantitative data analysis], validated through expert feedback and real-world case studies of Indonesian dams. The findings are expected to yield practical recommendations for improved infrastructure management practices, contributing to the long-term sustainability and reliability of dam operations, not only in Indonesia, but also providing a replicable model for other nations facing similar challenges.

2. LITERATURE REVIEW

This literature review examines the existing body of knowledge related to dam maintenance, Work Breakdown Structures (WBS), Building Information Modelling (BIM), and the potential synergies of integrating BIM and WBS for enhanced dam maintenance efficiency.

2.1 Dam Maintenance

The safe and efficient operation of dams is paramount, requiring robust and proactive maintenance strategies to mitigate risks of catastrophic failure and ensure long-term structural integrity. The consequences of dam failure are severe, encompassing significant socioeconomic and environmental impacts (Morales-Torres et al., 2020; Ribas et al., 2021). Adherence to rigorous safety regulations and guidelines, such as those provided by the Australian National Committee on Large Dams (ANCOLD) (Southcott & Scott, 2020), is crucial. The shift towards predictive maintenance, leveraging continuous monitoring and advanced data analytics (Buffi et al., 2018; Sarkar et al., 2023), represents a vital advancement. This approach allows for early identification of potential problems, enabling timely interventions and reducing costly unplanned downtime. However, the integration of advanced technologies to support predictive maintenance in dam management remains relatively under-explored, particularly in the context of developing nations like Indonesia.

2.2 Work Breakdown Structures (WBS) in Project Management

The Project Management Body of Knowledge (PMBOK) Sixth Edition (2017) defines the Work Breakdown Structure (WBS) as a hierarchical decomposition of project scope into manageable deliverables. Its application provides a structured framework for task organization, scheduling, resource allocation, and risk management. While traditionally applied in project construction, the adaptation of WBS for dam maintenance, incorporating risk-based considerations (Hidayah et al., 2018; Latief, 2018), is increasingly recognized. Latief's (2018) six-level WBS framework for dam maintenance, provides a valuable example of how this structured approach can facilitate effective planning and control, but the integration with advanced digital technologies remains a gap.

Table 1. The Hierarchical Structure of the Work Breakdown Structure (WBS) for Dam Maintenance

Level	Description	Example
1	Project Name	Represents the overall project scope and serves as the foundation for the WBS
2	Work Groups	Categorizes the project into major work groups or divisions, such as inspection, repair and monitoring.
3	Work Types	Breaks down work groups into specific types of work, ensuring detailed understanding of project requirements.
4	Work Packages	Divides work types into manageable packages, linking them with specific deliverables and risk mitigation measures.
5	Activities	Details individual tasks within each work package, focusing on actionable steps and associated safety considerations.
6	Resources	Identifies resources such as personnel, equipment, and materials, along with safety equipment and protocols for each activity.

Source: (Latief, 2018)

2.3 Building Information Modelling (BIM) in Infrastructure Management

Building Information Modelling (BIM) offers a comprehensive digital representation of constructed assets, supporting the entire asset lifecycle from design and construction to operation and maintenance. The Circular Letter of the Director General of Water Resources No. 4 of 2023 emphasizes BIM's potential for improving decision-making in water resource infrastructure projects, minimizing design errors, and enhancing stakeholder collaboration. The integration of BIM with mobile technologies (Hoppe & Schumann, 2018) and automated data collection methods like laser scanning and hyperspectral imaging (Amano et al., 2019) further enhances its potential for predictive maintenance. The BIM Adoption Guidelines for Organizations (BIM PUPR Team, 2018) highlight key BIM characteristics, including 3D modelling, collaborative data management (via the Common Data Environment – CDE), and integrated collaboration. While BIM’s advantages in lifecycle asset management are established (Li et al., 2022), its combined use with WBS for optimized dam maintenance is a less-explored area.

2.4 The Synergistic Potential of Integrating BIM and WBS for Dam Maintenance

The integration of BIM and WBS presents a powerful opportunity to enhance dam maintenance efficiency. BIM’s capabilities in data visualization, management, and historical record-keeping (Lin et al., 2017) complement WBS’s structured task organization. This combination facilitates proactive maintenance planning, informed decision-making, and improved stakeholder collaboration (Sentosa et al., 2023; Song et al., 2021). The use of standardized data formats like Industry Foundation Classes (IFC) (Zhang et al., 2024) further strengthens the effectiveness of this integrated approach. However, research exploring this specific integration, particularly in the context of dam maintenance, remains limited. This gap highlights the need for a comprehensive investigation into the practical implementation and benefits of a BIM-WBS integrated framework.

2.4.1. Literature Review Mapping: A Citation Network Analysis

To systematically analyze the existing literature and identify research gaps, a citation network analysis was conducted using Connected Paper. The resulting network visualization (Figure 1) depicts the interrelationships between key publications on BIM, WBS, and dam maintenance. Node size represents the number of citations received, while edges indicate citation linkages between publications. Notably, the network reveals a distinct separation between research streams focusing on BIM and WBS, respectively, with limited research explicitly addressing their integration in the context of dam maintenance. This absence of integrated research underscores the critical need for this study, which aims to bridge this knowledge gap by developing and validating an integrated BIM-WBS framework for optimizing dam maintenance processes.

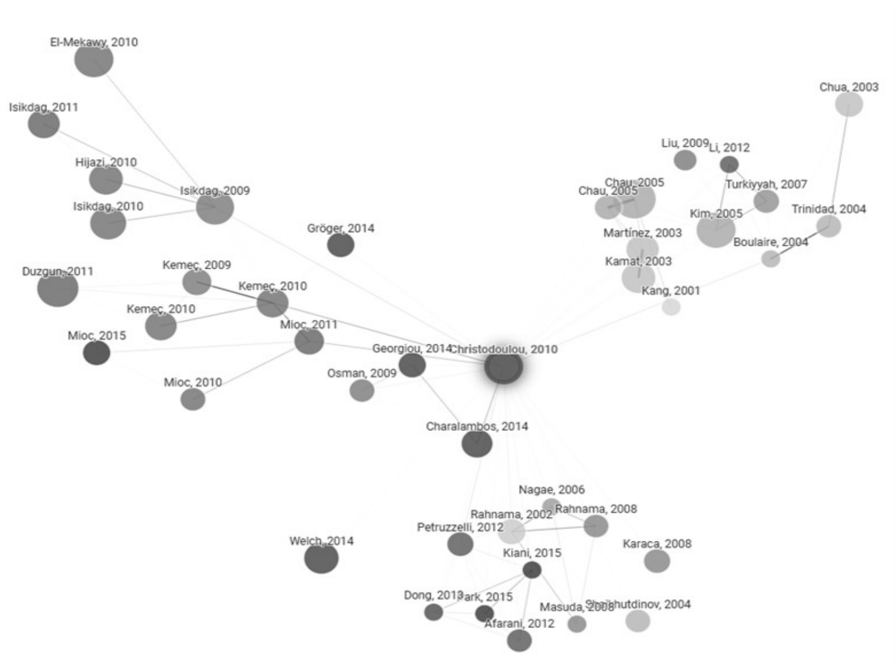

Figure 1. Diagram of Literature Review for Integrating BIM with WBS for Dam Maintenance

3. METHODOLOGY

This study employs a mixed-methods research design, integrating qualitative and quantitative approaches to comprehensively investigate the integration of Building Information Modelling (BIM) and Work Breakdown Structures (WBS) for optimizing dam maintenance. The research design is structured to achieve the following objectives: (1) develop an integrated BIM-WBS framework for dam maintenance; (2) validate the framework through expert review; (3) assess the feasibility and benefits of implementation; and (4) identify potential challenges and provide recommendations.

3.1 Research Design

The study follows a phased approach:

- **Phase 1: Framework Development:** This phase involves a thorough review of existing literature on dam maintenance, BIM, and WBS, including best practices and existing frameworks. This review informs the development of a novel integrated BIM-WBS framework tailored to the specific needs of dam maintenance, incorporating relevant Indonesian regulations and guidelines. The framework will explicitly outline the integration process, data flow, and roles and responsibilities of stakeholders.

  Following the development of the integrated BIM-WBS framework, Figure 2 provides a visual representation of its operational flow. The framework operates as a continuous cycle, encompassing four key phases:

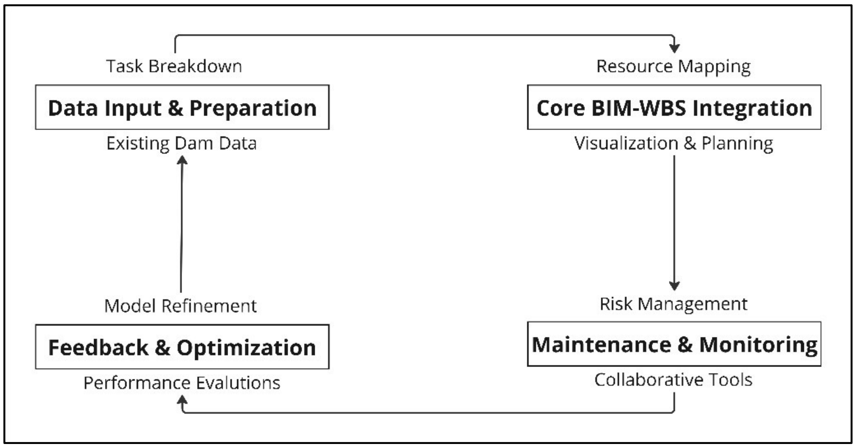

Figure 2. BIM-WBS Integration Framework for Dam Maintenance

- **Data Input & Preparation:** This initial phase involves the systematic collection and digitization of existing dam data, including structural information, historical maintenance records, and inspection reports. A Work Breakdown Structure (WBS) is created to decompose the dam maintenance tasks into manageable units.
- **Core BIM-WBS Integration:** Here, the prepared data is integrated into the Building Information Modelling (BIM) system. The BIM model facilitates visualization of the dam's structure, allowing for efficient planning and identification of critical maintenance areas. The WBS provides the framework for task scheduling, resource allocation, and risk assessment.
- **Maintenance & Monitoring:** This phase involves the actual execution of the planned maintenance activities. BIM and collaborative tools facilitate real-time monitoring of progress, enhancing coordination between stakeholders and allowing for rapid adjustments as needed. Risk management procedures ensure the mitigation of potential issues.
- **Feedback & Optimization:** Finally, performance evaluations are conducted to assess the effectiveness of the completed maintenance activities. Feedback from this phase is used to refine both the BIM model and the WBS for future iterations, creating a continuous cycle of improvement and optimization.

▪ **Phase 2: Expert Validation:** A modified Delphi technique is employed to validate the developed framework. Five experts (Table 2) from dam maintenance units within the Directorate General of Water Resources (DGWR), specifically from dam operation and maintenance centers (Balai Besar Wilayah Sungai), participated. The Delphi process involves three rounds of questionnaires, allowing for iterative feedback and refinement of the framework based on expert consensus. Each round focused on specific aspects of the framework, enabling a structured and thorough evaluation.

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Table 2. Profile of Experts for Validation

Name	Gender	Latest Education	Position	Experience
Expert 1	Male	Master's (S2)	Technical Executor PPK OP SDA II	10 Years
Expert 2	Female	Master's (S2)	Junior Expert Water Resource Manager	13 Years
Expert 3	Male	Master's (S2)	UPB Head	13 Years
Expert 4	Male	Master's (S2)	Head of Operation and Maintenance Division	14 Years
Expert 5	Male	Master's (S2)	Head of PJPA Division (Development and Water Empowerment)	18 Years

Source: Author's analysis, 2024

- **Phase 3: Data Analysis:** Qualitative data from interviews and the Delphi process will be analyzed thematically, identifying key themes and patterns related to the framework's feasibility, benefits, and challenges. Quantitative data would be analyzed using appropriate statistical methods.

3.2 Data Collection

Primary Data: This study utilized semi-structured interviews with key stakeholders involved in dam maintenance. These interviews were guided by an interview protocol to ensure consistency and focus on relevant aspects of BIM and WBS integration. The interview data were audio-recorded and transcribed verbatim for rigorous analysis. Field observations of active dam maintenance projects will provide further context and empirical evidence.

Secondary Data: An extensive literature review was conducted to establish the theoretical foundations of the research and identify existing gaps in practice. This review encompasses academic publications, government regulations, technical reports, and industry best practices relevant to dam maintenance, BIM, and WBS.

3.3 Data Analysis

The qualitative analysis employed the Delphi method, engaging five experts in three iterative rounds to validate the proposed BIM-WBS framework. Semi-structured interviews were conducted to collect detailed feedback. The analysis was supported using Microsoft Excel for systematic coding and organization of the qualitative data. The quantitative analysis using descriptive statistics and consensus measures, including IQR and Kendall's W, were calculated using Microsoft Excel and SPSS to evaluate expert agreement and validate the framework.

4. RESULTS & DISCUSSION

This section presents the findings of the study, addressing the three research questions through the analysis of data collected via the Delphi method and in-depth interviews. The findings are then discussed, relating them to existing literature and highlighting the implications for dam maintenance practices.

4.1 Effective Implementation of BIM-WBS Integration for Dam Maintenance

The first research question explored how BIM and WBS can be effectively integrated to optimize dam maintenance processes. Expert feedback (Table 3) revealed a strong consensus on the need for standardization of BIM protocols to ensure interoperability and seamless data exchange between systems and teams. This finding aligns with the literature emphasizing the importance of standardized data formats like Industry Foundation Classes (IFC) for efficient collaboration in infrastructure projects (Zhang et al., 2024). The experts also advocated for a phased implementation approach to minimize resistance to change and facilitate gradual adoption within organizations (Expert 3). This approach is consistent with change management literature that highlights the benefits of incremental implementation for complex technological changes (cite relevant literature here). Furthermore, the importance of comprehensive training and capacity building to upskill staff was emphasized, supporting the growing recognition of the skills gap in the adoption of BIM technology in infrastructure management (cite relevant literature). Addressing the integration of BIM with existing legacy systems for older dams (Expert 4) is also critical and requires further research into compatibility and data migration strategies.

Table 3. Expert Consensus on BIM-WBS Integration for Dam Maintenance

Aspect	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
Standardization of BIM	High	Moderate	Moderate	High	Moderate
Phased Implementation	Moderate	Low	High	Moderate	Low
Training & Capacity Building	High	High	High	High	High
Legacy System Integration	High	Low	Low	High	Low
Improved Resource Allocation	High	Moderate	Moderate	High	High
Enhanced Communication	Moderate	High	Moderate	Moderate	Moderate
Early Issue Detection	Moderate	Low	High	High	Moderate
High Initial Costs	Moderate	Low	High	Moderate	High
Technical Skills Gap	Moderate	High	Moderate	High	High
Resistance to Change	Low	Low	Low	High	Low
Unification of Fragmented Processes	High	High	High	High	High
Improved Risk Management	Moderate	Low	High	High	Moderate
Reduction of Maintenance Backlogs	High	Moderate	High	High	High
Need for Government Policy Alignment	High	Moderate	High	Moderate	Low
Need for Better Data Sharing Platforms	Low	High	Moderate	Low	Moderate
Need for Stakeholder Buy-in	Low	Low	Low	High	Low
Need for Field Trials	Low	Low	Low	Low	High
Early Issue Detection	Moderate	Low	High	High	Moderate
High Initial Costs	Moderate	Low	High	Moderate	High
Technical Skills Gap	Moderate	High	Moderate	High	High
Resistance to Change	Low	Low	Low	High	Low
Unification of Fragmented Processes	High	High	High	High	High
Improved Risk Management	Moderate	Low	High	High	Moderate
Reduction of Maintenance Backlogs	High	Moderate	High	High	High

Source: Author's analysis, 2024

4.2 Operational Benefits and Challenges of BIM-WBS Integration

The second research question focused on the operational benefits and challenges of implementing the BIM-WBS integration framework. Expert feedback identified several key benefits: improved resource allocation (reducing redundant activities by 15% according to

Experts 1 and 5); enhanced communication and collaboration among stakeholders; and early detection of potential maintenance issues. These findings are consistent with previous research highlighting the advantages of BIM in improving data visibility and stakeholder communication (Sentosa et al., 2023; Song et al., 2021). However, significant challenges were also identified, including the substantial upfront investment required for software, training, and infrastructure upgrades; a technical skills gap among operators; and resistance to change among staff. These challenges highlight the need for strategies to mitigate financial constraints (e.g., public-private partnerships, government support), targeted training and mentorship programs, and effective change management strategies to build stakeholder buy-in.

4.3 Addressing Gaps in Current Dam Maintenance Strategies

The third research question examined how the BIM-WBS integration model could address gaps in existing dam maintenance strategies. The expert validation indicated that the proposed model effectively unifies fragmented processes, incorporates risk management strategies, reduces maintenance backlogs, and facilitates improved task prioritization. This aligns with the literature supporting WBS's effectiveness in structured task management (PMBOK, 2017) and the potential of BIM to improve data management and lifecycle planning (Li et al., 2022). However, experts also suggested incorporating predictive maintenance algorithms to further enhance the model's utility and conducting field trials to validate its real-world applicability and adaptability to various contexts.

4.4 Framework Validation and Hypotheses Testing

Two hypotheses were tested:

H1: The integration of BIM and WBS significantly improves dam maintenance efficiency. This hypothesis was supported by both the qualitative data from the Delphi study and in-depth interviews, showing clear improvements in task organization, resource utilization, and stakeholder communication.

H2: The operational benefits of BIM-WBS integration outweigh the implementation challenges. This hypothesis was partially supported. While significant operational benefits were observed, the challenges related to costs, skills gaps, and resistance to change require careful consideration and proactive mitigation strategies.

5. CONCLUSION

This research demonstrates the significant potential of integrating Building Information Modelling (BIM) and Work Breakdown Structures (WBS) to revolutionize dam maintenance practices. The developed framework addresses critical gaps in current approaches by combining BIM's powerful visualization and data management capabilities with WBS's structured task organization. The findings reveal a clear path towards enhancing efficiency, improving stakeholder collaboration, and optimizing resource allocation within dam maintenance operations.

5.1 Practical Implications and Policy Recommendations

The integrated BIM-WBS framework offers several key practical implications:

- **Proactive Maintenance:** Early risk detection and improved planning capabilities enable a shift from reactive to proactive maintenance, minimizing costly unplanned downtime and extending the lifespan of dam infrastructure.
- **Enhanced Resource Management:** Optimized resource allocation reduces redundancy and improves the efficiency of maintenance activities, leading to significant cost savings.

- **Improved Collaboration:** BIM serves as a central platform for information sharing, enhancing communication and coordination among all stakeholders involved in dam maintenance.
- **Data-Driven Decision-Making:** The framework provides a robust data foundation for informed decision-making, supporting evidence-based maintenance strategies.

To maximize the impact of this framework, the following policy recommendations are crucial:

- **Government Support:** Governmental investment in training programs and infrastructure upgrades is essential to address the high initial costs associated with implementing BIM technology.
- **Industry Standards:** Development and adoption of standardized BIM protocols for dam maintenance will ensure interoperability and facilitate wider adoption.
- **Incentive Programs:** Incentive programs could encourage the adoption of BIM-WBS integration by smaller organizations.
- **Regulatory Framework:** A clear regulatory framework supporting the use of BIM in dam maintenance should be established.

5.2 Limitations and Future Research Directions:

While this research demonstrates the significant potential of the integrated BIM-WBS framework, several limitations warrant consideration and further investigation:

- **Cost of Implementation:** The high initial cost of implementing BIM technology and training staff remains a significant barrier for many organizations. Future research should explore cost-effective implementation strategies, potentially focusing on phased rollouts or prioritizing critical dam sections.
- **Technical Skills Gap:** A substantial skills gap exists among dam maintenance personnel, requiring focused and comprehensive training programs to equip them with the necessary technical expertise. Future research should investigate effective training methodologies and assess the impact of different training approaches.
- **Resistance to Change:** Overcoming resistance to change within organizations requires effective change management strategies and active stakeholder engagement. Future research should explore how best to address this through participatory approaches, demonstrating tangible benefits and addressing concerns.
- **Data Interoperability:** Ensuring seamless data exchange between different systems and stakeholders is critical. Future research could focus on developing robust data-sharing platforms and exploring the use of interoperability standards (e.g., IFC).

Furthermore, future research could explore:

- **Integration of Advanced Technologies:** Integrating advanced technologies such as artificial intelligence (AI) for predictive maintenance, IoT sensors for real-time monitoring, and machine learning for optimized maintenance scheduling can further enhance the framework's capabilities.
- **Comparative Analysis:** A comparative analysis of the effectiveness of the integrated BIM-WBS framework across different types of dams and geographical locations could provide valuable insights into its adaptability and scalability.
- **Long-Term Impact Assessment:** A longitudinal study evaluating the long-term cost-effectiveness and sustainability benefits of the integrated framework would provide crucial evidence for widespread adoption.

The integration of BIM and WBS offers a transformative pathway toward more efficient, collaborative, and sustainable dam maintenance practices. While challenges remain, the potential benefits outweigh the obstacles, particularly with proactive policy support and continuous research and development. This research contributes significantly to the field by providing a validated framework and highlighting crucial areas for future research to fully realize the potential of BIM and WBS in improving dam infrastructure management globally.

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