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Posted Date: 13 December 2024

doi: 10.20944/preprints202412.1120.v1

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Article

A BIM Enabled Workflow for Rehabilitation of Heritage Steel Bridges

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Abstract: The rehabilitation of heritage steel bridges rises specific challenges due to their historical significance and structural complexity. This paper explores the transformative potential of Building Information Modelling (BIM) workflows in addressing these challenges, with a focus on seamless information transfer throughout a bridge's lifecycle enabling infrastructure owners, particularly national road authorities, to leverage enhanced decision-making capabilities. The digitalization of bridge-related information can further enable the creation of digital twins for predictive maintenance, optimized resource allocation, and strategic planning for rehabilitation works. The approach proposed within this paper, including the definition and outline of Information Requirements, can be adapted by authorities and used as the backbone of efficient data management. Clearly defined information requirements ensure alignment between organizational objectives, asset-level needs, and project-specific deliverables, fostering a holistic information workflow. A key contribution of this research is the development of a template for Information Delivery Specification (IDS), that in intended to provide a clear framework for data exchange and quality control across all project phases. This technical document is meant to ensure seamless integration of technical and historical data into a centralized digital repository and to support the operational needs, during project implementation, and heritage preservation needs, on project hand-over. Additionally, present article explores the technical aspects of rehabilitation, including the structural assessment and strengthening strategies, while emphasizing that these should be directly integrated within the BIM workflow.

Keywords: BIM workflow; heritage steel bridges; bridge rehabilitation; infrastructure sustainability; centralized data management

1. Introduction

Transportation infrastructure is the cornerstone of economic growth, national security, and social well-being. Its reliability and safety exploitation directly impact the goods and people movement, fuelling economic prosperity and societal development. However, as these systems age, while the mobility demand grows, maintaining and rehabilitating transportation networks has become a critical challenge, driving the need for innovative, efficient, and cost-effective solutions.

Unlike buildings, transportation infrastructure, comprising roadways, utilities, and environmental assets, is inherently expansive and interconnected [1]. Three out of five domains within transportation infrastructure are characterized by a mesh network of assets, where longitudinal structures like roads, railways and pipelines connect point structures such as bridges and intersections. This unique configuration generates significant differences in project breakdown structures compared to building projects. The expansive size of transportation networks necessitates greater reliance on Geographic Information Systems (GIS) to map and manage these assets. Moreover, transportation projects often involve a more mature asset management process, emphasizing the importance of non-graphical data and its meaningful integration into project models. Furthermore, data structures in transportation projects are more varied and interconnected

are require a strong focus on integrating diverse information sources. This requirement is paramount for the collaborative teams, often larger and more complex, to be able to account for the expansive scope of transportation projects.

A key component of road infrastructure is represented by bridges. Emerging in the late 18th century with the construction of the Iron Bridge in Coalbrookdale, steel structures have evolved through distinct phases—cast iron, wrought iron, and mild steel, the latter becoming dominant. For Europe, a significant role in this evolution was played by Romania, with its steel industry taking root in the 18th century. By the second half of the 19th century, the Austrian Railways Company, STEG, had introduced modern steel production technologies in the western region of Romania, at Reșița (Reschitza). The riveted steel bridges produced here, stand as an innovations' testament to the industrial revolution. This period saw not only advancements in steel elaboration methods but also a broader recognition of steel's potential for infrastructure, paving the way for the widespread use of this material. Recognizing that no structure is built to last indefinitely, developed societies have embraced the importance of maintaining architectural heritage to preserve cultural identity while ensuring functional infrastructure. Aligned with this, the rehabilitation of heritage steel bridges has become a cornerstone of sustainable development and cultural preservation. Furthermore, refurbishing these structures aligns with the principles of sustainability by reducing the need for new materials and construction, limiting the CO₂ emissions, while retaining historical and aesthetic value.

To address the pressing challenges of ageing structures and enable better decision making, while accounting for the multidimensional complexity, advanced technologies are being increasingly integrated into infrastructure management. Among these, Building Information Modelling (BIM) has emerged as a revolutionary digital process, transforming the way we approach design, construction, and rehabilitation. It facilitates the definition of information requirements, the creation, management, and exchange of detailed digital representations of physical and functional characteristics of assets throughout their lifecycle. By enhancing efficiency in project development and implementation and by fostering collaboration, BIM offers a robust solution for streamlining the information flow during the rehabilitation of heritage steel bridges, supporting the cultural heritage preservation and sustainable development.

Despite its success in the building sector, the adoption of BIM in transportation infrastructure has been slower and less uniform [2]. Authorities, industry and academia alike are increasingly focusing on the implementation of BIM in non-building civil infrastructure, including bridges, tunnels, and railways. However, much of this effort lacks a structured framework tailored specifically to the unique challenges and requirements of transportation systems. Currently, there is a notable gap in the development of BIM workflows for the rehabilitation of ageing transportation infrastructure, especially steel bridges, which form a critical subset of these systems. Addressing this gap requires an understanding of both the initial costs, operational and maintenance costs, together with the substantial long-term benefits of implementing a BIM workflow. While the upfront investment in BIM may appear significant during initial project phases (i.e., current estimations brings BIM use within projects to the level of design costs), research consistently shows that the long-term benefits far surpass these costs, often leading to savings ranging from 1.5% to 15% [3], with a 5% to 9% [4] cost reduction during the construction phase only due to reduced change orders and rework. Additionally, BIM workflows enable the incorporation of Lifecycle Costs (LCC) considerations into the design phase, adding significant value. This approach enables a thorough analysis of costs throughout the asset's lifecycle, spanning from planning, design, material selection, construction, operation, maintenance, and eventual decommissioning. LCC integration within the BIM workflow supports informed decision-making, optimizing outcomes for both cost and performance. For instance, prioritizing durable, corrosion-resistant materials might increase upfront expenses but drastically reduces maintenance needs and repair costs over time. Additionally, designing with ease of access for inspections, enabled by a 3D modelling and detailing with special care for soft collisions, simplifies routine maintenance, cutting labour and equipment expenses.

Figure 1 (an adaptation of the LCC concept [5]) illustrates two contrasting approaches to project cost management over the lifecycle of an asset. The graph on the left represents the scenario where

sharp cost increases due to unplanned rehabilitation interventions and repairs, while the graph on the right demonstrates a smoother, more predictable distribution of costs stemming from a planned and proactive lifecycle asset management. The unexpected spikes in costs shown on the left, will likely result from reactive maintenance strategies, where issues are addressed only after they arise. This approach often leads to higher expenditures in the form of emergency repairs, operational disruptions, and potentially large-scale replacements that could have been avoided with earlier, planned intervention. Such unplanned costs strain budgets, disrupt operational schedules, and can compromise the asset’s performance and safety over time. In addition, each intervention usually includes an asset down-time, with traffic stops, deviations or, at least, restrictions. In contrast, the right-hand side reflects a strategic approach, where costs are evenly distributed over the asset’s lifecycle. Planned maintenance, informed by LCC considerations and a clear information flow enabled by BIM process, allows for early identification and mitigation of potential issues. Such proactive strategies (i.e., use of more durable materials, implementation of advanced monitoring technologies, coupled with a clear schedule of regular inspections) ensure long-term financial predictability, asset reliability and operational safety.

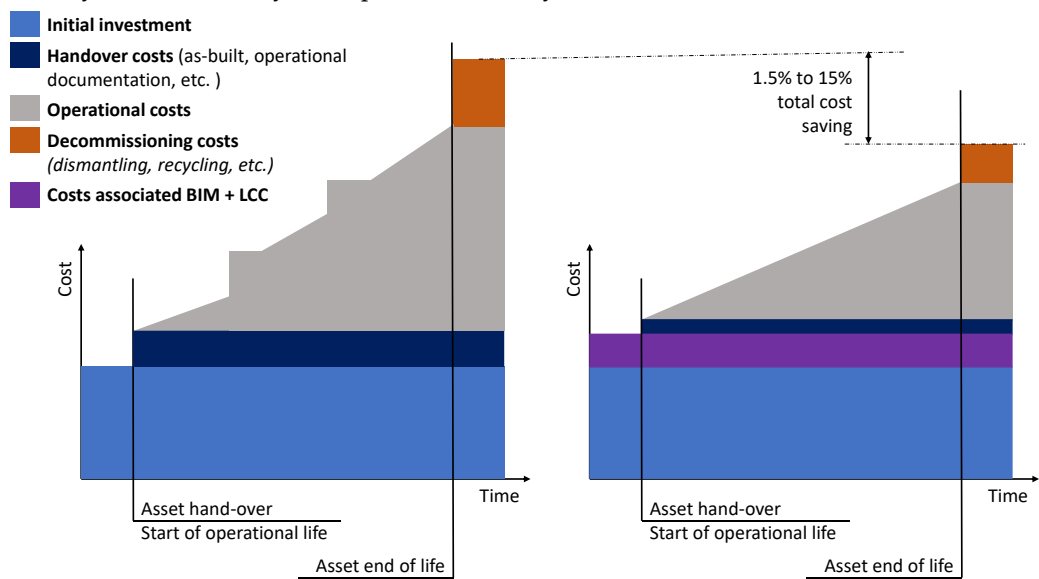


Figure 1. Life-cycle costs.

The comparison presented in Figure 1, highlights the critical role of integrating lifecycle management principles into project planning and execution, supported by a robust information management system i.e., BIM enabled LCC. A proactive strategy can yield significant cost savings, enhanced asset resilience with improved operational performance, fully aligned with global sustainability objectives. Transitioning from traditional documentation to BIM-enabled digital workflows offers significant advantages beyond asset management, operation, and maintenance. This shift provides stakeholders with both financial and technical benefits while streamlining data collection and storage processes. Enhanced data reliability reduces the cost, time, and overall effort during the operational phase of projects, while creating a solid foundation for detailed analyses that can, in turn, lead to future cost savings. For public authorities, custodians of transportation infrastructure, the integration of Lifecycle Costing (LCC) within the BIM framework empowers informed decision making and more effective resource allocation. Furthermore, aligning BIM processes with sustainability goals ensures that infrastructure investments maximize public value throughout the asset’s entire lifecycle [6].

2. Current State of the Art

Typically, the rehabilitation process starts with a triggering event, such as i) identification of structural issues during routine inspections or noticeable signs of wear, such as corrosion or cracks,

ii) following natural disasters, increased traffic loads as a change of standards, or changes in safety regulations or iii) mandate assessments as part of infrastructure upgrade strategies. The decision to initiate an evaluation process is often made by public agencies or bridge operators, with the national legal framework governing the subsequent steps. For instance, in most jurisdictions, bridge evaluations must align with national safety standards and engineering codes. Once the rehabilitation need is identified, a legal process, including the procurement of services, approval of budgets, and the establishment of project timelines, guides the rehabilitation journey. The rehabilitation of existing steel bridges is a critical process, requiring a balance between traditional techniques and the adoption of emerging technologies to ensure structural integrity, safety, and longevity. As infrastructure ages, steel bridges are increasingly subject to rehabilitation interventions to address deterioration, adapt to evolving regulatory requirements, and meet present demands for mobility, functionality, and sustainability. Historically, the rehabilitation of steel bridge relies on manual on-site inspections. While usually effective, these approaches are labour-intensive and highly dependent on personal experience, leading to subjective assessments.

2.1. Traditional Methods and Emerging Technologies for Bridge Inspection

Nowadays, engineering processes related to infrastructure engineering still rely heavily on manual processes of qualified bridge engineers. On-site inspections form the backbone of these methods, focusing on the assessment of critical elements within the structure, including decks, beams, joints, and supports. Specialists and technical experts visually examine these components searching for signs of deterioration (e.g., corrosion, cracking, spalling, and misalignment), while also evaluating the bridge's load-bearing capacity to identify weaknesses that require intervention. While visual inspection is usually a straightforward and cost-effective process, reliance on subjective assessments and the potential for human error limits its efficiency. Hidden damage (e.g., internal cracks or flaws within elements' material) can go unnoticed without additional diagnostic tools. To address these gaps, specialized techniques, such as i) Non-Destructive Testing (NDT) like ultrasonic testing, magnetic particle inspection, and radiographic testing employed to detect internal defects and assess material properties without damaging the structure; ii) simulated or live load testing to evaluate the bridge's performance under controlled conditions and help engineers estimate the real loadbearing capacity and determine the load – deflection curve; and/or iii) hammer sounding used to identify delamination in elements by listening to changes in sound pitch when tapping the surface.

However, on-site inspections often rely heavily on the personal expertise and subjective assessments of bridge specialists and/or technical experts. While these assessments are effective for identifying visible issues, it has notable limitations that include the difficulty in detecting hidden defects and the labour-intensive nature of manual, in-person, evaluations. To address these shortcomings, advanced technologies are increasingly being employed to complement traditional methods. This integration combines the practicality and familiarity of manual inspections with the precision and efficiency of modern tools. The result is a more comprehensive approach leading to a better understanding of a bridge's condition, enhancing the ability to early detect potential issues, significantly improving maintenance and rehabilitation processes.

Several emerging technologies can be particularly transformative for bridge operation, maintenance, rehabilitation, and ultimately, overall lifecycle management. Building Information Modelling (BIM) enhances collaboration among all stakeholders, enabling the development of information rich 3D models to reduce inefficiencies and communication gaps. In addition, several other technologies can be considered to significantly improve bridge operation, maintenance, and rehabilitation. These include advanced materials, smart construction technologies, digital twins combined with bridge management systems (BMS), and structural health monitoring systems, all of which streamline and enhance the overall efficiency of bridge related processes. The adoption of smart construction methods, including artificial intelligence (AI), drones, and LiDAR sensors, is revolutionizing bridge assessments. For example, drones equipped with sensors enable precise inspections in hard-to-reach areas, while 3D scanning [7], LiDAR and GPS ensure accurate site positioning. Moreover, integrated systems like SCADA (Supervisory Control and Data Acquisition)

provide real-time monitoring of structural health, offering early warning signs of deterioration or damage. Digital twins can be employed to create virtual representations of physical assets, enabling real-time analysis and predictive maintenance.

Modern Bridge Management Systems (BMSs) integrate these technologies to enhance decision-making across a bridge's lifecycle. As highlighted by the literature [8], such systems allow for efficient condition assessments and the optimization of maintenance strategies based on structural health and risk analyses. Often, BMSs limit their scope to 4 modules [9] i.e., i) data management, dealing with data about bridges and the status of their components; ii) diagnosis, consisting of condition rating and deteriorating assessment; iii) prognosis, gathering all the activities connected to the prediction of future bridge conditions; and iv) decision-making, identifying optimal management actions, guiding decisions based on engineering judgment. The modules are generally interconnected. While diagnosis and prognosis rely on data pertaining to bridges and their components, the decision-making is influenced by the outcomes of diagnosis and prognosis and can also impact data management.

Structural Health Monitoring (SHM) systems deploy sensors [10] (e.g., fiber optic sensors (FOS), piezoelectric sensors, vision-based displacement measurement systems, and magneto strictive sensors (MsS)) to monitor factors like stress, structural vibration, and/or temperature. These systems continuously track structural health, allowing operators to identify damage early and mitigate risks. For example, MEMS (Micro-Electro-Mechanical Systems) sensors are increasingly used for their precision and compactness, enabling data capture on bridge behaviour over time.

The integration of Advanced Computer-Aided Design (CAD) tools with Finite Element Analysis (FEA) capabilities provides engineers with a powerful framework for designing and evaluating bridges [11,12], especially in scenarios requiring extensive rehabilitation. Modern CAD tools allow engineers to create detailed and accurate 3D representations of bridges, incorporating geometric, material, and even environmental factors. When combined with advanced FEA capabilities, these models can simulate a structure's behaviour under various conditions, such as multiple load distribution, environmental stresses, and potential failure scenarios. Using advanced numerical models, the CAD-FEA approach enables bridge specialists to i) identify weak points before the rehabilitation begins and ii) evaluate multiple design alternatives and test extreme conditions without physical prototyping. The added value of these tools can be further augmented by incorporating feedback from real-world bridge. Leveraging the capabilities of IoT enabled monitoring systems [2] that provide reliable data on stresses, vibrations, and/or environmental conditions on existing bridges, digital models are updated and augmented to reflect actual conditions rather than purely theoretical scenarios.

2.2. Traditional Heritage Steel Bridge Rehabilitation Process

As mentioned before, rehabilitation of heritage steel bridges presents a range of technical challenges primarily driven by structural deterioration, corrosion, and fatigue. Over time, these factors compromise the integrity and performance of bridge components, posing risks to safety and functionality. As the structure is subjected to loads from traffic and environmental forces, critical structural elements are subjected to wear and tear, weakening their capacity to withstand additional stress. Cracks, deformation, and material thinning are common issues that arise and requires rigorous inspection and repair strategies. For steel bridges, corrosion remains one of the most persistent challenges, especially in joints and connection points. Prolonged exposure to moisture and de-icing salts accelerates material degradation, compromising both structural integrity and durability. Corroded elements reduce load-bearing capacity, increasing the vulnerability of the structure. This degradation often complicates maintenance and repair efforts, as the weakened components carry a heightened risk of further damage during intervention. Corrosion can cause additional issues due to stuck bearings, that are meant to allow free movement (e.g., a simply supported bridge, may be transformed into a double-pinned one). This unintended shift alters load distribution, increasing stress on certain components (e.g., piers), potentially leading to unaccounted failure modes. Another key issue of steel bridges is posed by fatigue (i.e., the repeated stress cycles from dynamic loads,

leading to micro-cracks that propagate over time). This issue is particularly critical in bridges with high traffic volumes or those exposed to heavy vehicles. Fatigue-related failures are challenging to predict, requiring advanced monitoring techniques and detailed modelling to identify vulnerable areas.

The rehabilitation of heritage steel bridges involves complex processes that require the integration of diverse data sources, stakeholder collaboration, and compliance with technical standards. Efficient and effective information workflows are crucial to streamline these activities, to reduce uncertainties, and ultimately enhance decision-making. The general process is presented in Figure 2 and focuses on two key aspects i) structural integrity, emphasizing the technical assessments and interventions required to ensure the safety and functionality and ii) compliance with standards, to ensure that all legal and engineering requirements are met.

The rehabilitation process starts with the identification of intervention needs, often prompted by routine inspections, structural performance reviews, or general safety concerns, as presented before. Next, Phase 1 starts. Within this phase, a preliminary on-site visual inspection is performed that allows studying the bridge's current state, followed by a thorough review of historical records, including design documents, maintenance logs, and past inspection reports, to piece together its operational history. Putting together all these details, a preliminary technical assessment is performed that focuses on visible issues such as corrosion, cracking, or noticeable deformations. If critical problems are identified, immediate safety measures are implemented, while further investigations are performed.

Next, Phase 2 commences. The available information is assessed to determine whether it provides sufficient information to correctly evaluate the bridge's condition. When information is lacking, or it is unreliable, additional investigations are required. On this line, advanced technologies like laser scanning or drone surveys might be used to create precise geometric models, while detailed inspections with non-destructive testing methods, such as ultrasonic or radiographic tests, can offer deeper insights into the structure's material and overall health. Regarding material it must be mentioned that a wealth of experimental test results on heritage steel bridge materials has been accumulated over the years, resulting in a highly reliable and statistically robust database. This extensive body of data provides detailed insights into steel properties used in various periods, making it a valuable resource for assessing material performance. Given the database extent, performing new experimental tests on materials for existing bridges rarely changes the statistical understanding of their properties. Due to this, bibliographic research has become a reliable and common approach for material assessment, particularly for bridges whose construction period is well-documented. By referencing historical data and leveraging the wealth of experimental results available, the materials' behaviour can be accurately predicted, thus removing the need for additional testing. As a result, experimental tests are typically reserved for cases where unusual conditions, damage, or lack of historical documentation warrant additional investigation.

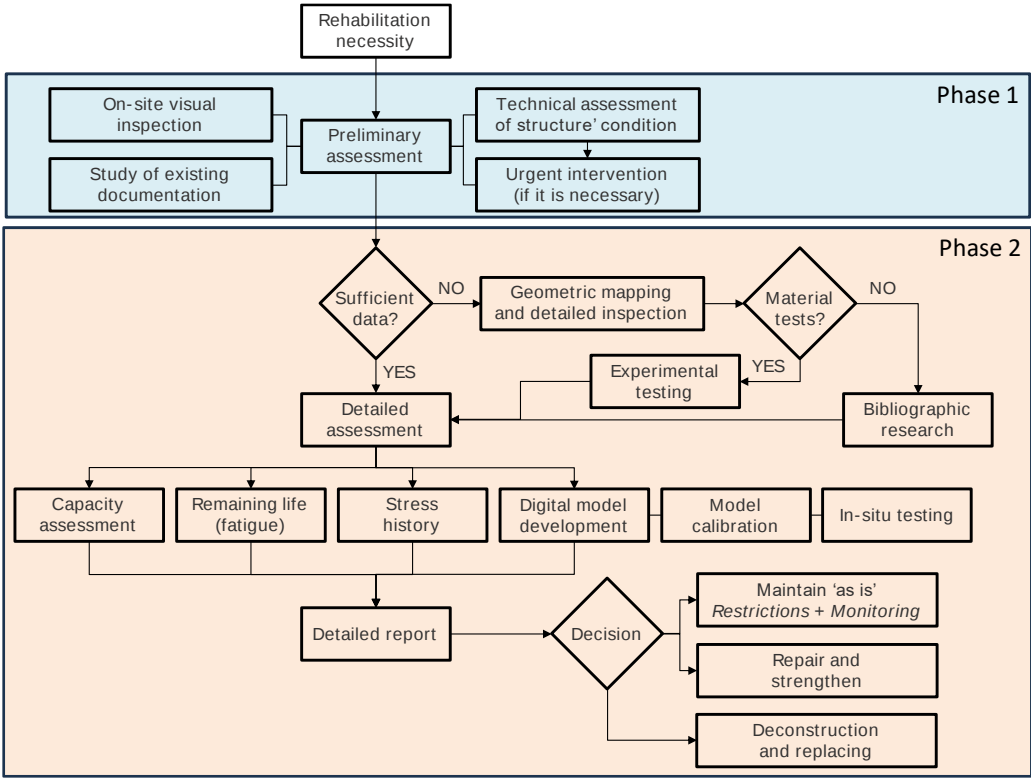


Figure 2. Technical process for rehabilitation of heritage steel bridges.

Once enough data has been collected, an exhaustive assessment is conducted. This includes the assessment of bridge’s load-carrying capacity, the analysis of its stress history, identification of areas most susceptible to failure and finally, the estimation of its remaining fatigue life. A CAD model of the bridge is usually developed, providing detailed insights in bridges’ behaviour under various conditions. To ensure accuracy, the digital model is developed accounting for geometric data mapped on-site, specific material properties, and is generally calibrated against on site tests. The results of such assessments are used to guide the next steps. If the structure is deemed safe, or it requires minimal intervention, it can remain operational under specific restrictions, supplemented by ongoing monitoring to ensure safety. For bridges requiring more significant attention, repair or strengthening strategies can be implemented to restore their full, or at least partial, functionality. For cases where the structure is severely damaged or the rehabilitation costs are prohibitive, the focus may shift toward planning and executing deconstruction and/or replacement. Alternatively, the bridge can be considered for repurposing e.g., converting a railway bridge for automotive use, an automotive bridge for pedestrian or cyclist traffic, or other adaptive reuse scenarios that align with the community’s needs.

Throughout the entire process, a technical report is developed, documenting findings, analyses, and recommendations to serve as a critical reference for stakeholders. In most cases, information exchange is conducted using traditional paper-based methods (or digitalized paper i.e., .pdf), and the technical documentation typically includes only the information mandated by law. While the focus remains on the technical aspects of rehabilitation, this workflow underscores the importance of comprehensive assessment and strategic decision-making to tackle the unique challenges associated with ageing steel bridges effectively.

3. The Information Management Framework

To overcome the limitations on information exchange posed by the traditional process, while keeping a thorough technical process in place, a BIM workflow should be considered. It should integrate structured processes and data management principles to align organizational objectives, asset operational and maintenance needs, and project-level objectives throughout the lifecycle. As

depicted in Figure 3, this approach is enabled by international standards, such as ISO 19650 [13] for information management, ISO 55000 [14,15] for asset management, and ISO 21500 [16] for project management to ensure consistency and interoperability across all project phases. It can be easily observed that the entire standard landscape is enabled by ISO 9001 [17], that ensures process quality, transparency, traceability, and accountability.

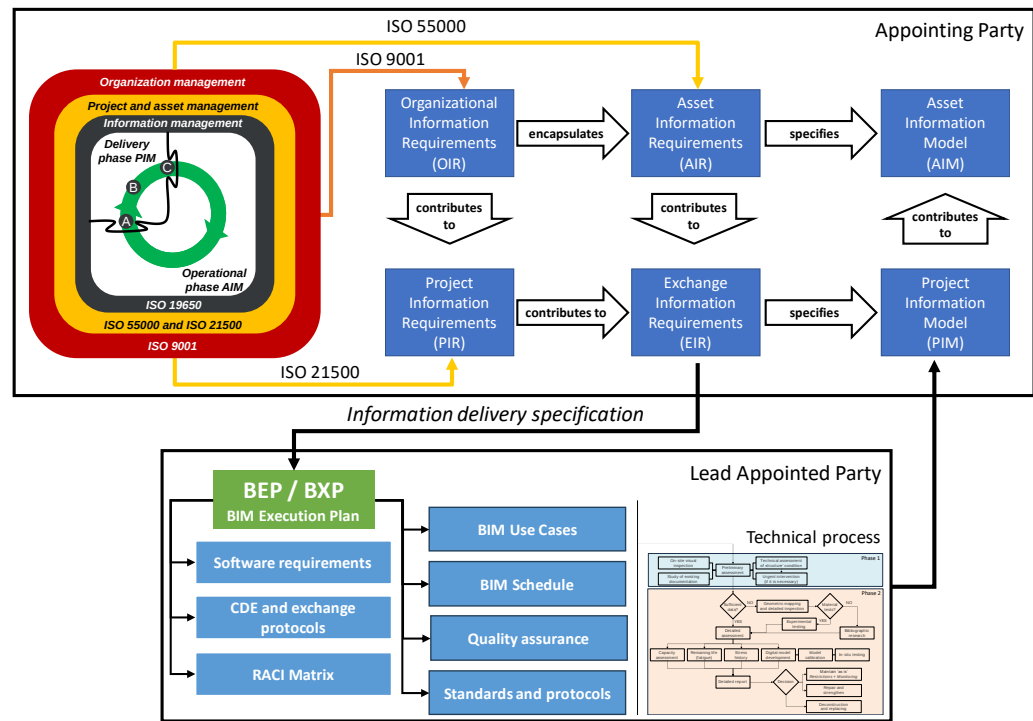


Figure 3. BIM enabled process for rehabilitation of heritage steel bridges.

According to ISO 19650, the process begins with the statement of need formulated by the appointing party (for example the client). It must ensure that the information requirements are clearly defined at the start of the project along with how the concepts and principles of information management are to be implemented and the benefits that are expected. Information management and associated processes can also be considered as far as they can be determined by the appointing party [18]. Next, each prospective lead appointed party (e.g., designer, main contractor) responds to these information requirements in their (pre-appointment) BEP (i.e., BIM execution plan) which includes their statements of capability and capacity to apply the ISO 19650. The appointing party considers the contents of each BEP, evaluates them and then selects the lead appointed party. During mobilisation (the initial project phase), the appointing party (for example the client), the lead appointed party (for example the contractor) and other appointed party/parties (for example the subcontractors) collaborate to agree key roles and responsibilities and to agree an IDP (i.e., Information Delivery Plan). Next, in accordance with ISO 7817 [19], these parties establish the level of information need required at every project stage and approval, authorisation and acceptance procedures. This enables the configuration and implementation of appropriate information management systems that must provide and consider the needs of the project team and stakeholders, the process of information delivery, the selection and use of appropriate technologies required for delivery.

At the beginning of the process, the appointing party clearly express the information requirements to other organisations and individuals through their exchange information requirements to specify or inform their work. A clear information hierarchy is linked to the project, asset(s) and organisational objectives, as shown in ISO 19650-1, Figures 2 and 3 of the present document.

Conducted by the appointing party or a party representing it, the development of Organizational Information Requirements (OIR), encapsulates the strategic goals (defined in

alignment with ISO 9001) and the organization information needs that are linked with the project. Next, the OIR informs the development of Asset Information Requirements (AIR), which further details the information required for effective asset management, contributing to the creation and maintenance of the Asset Information Model (AIM) during the operational phase. The development of the AIR, guided by ISO 55000, is aligned with the operational and maintenance requirements of the asset. At the project level, Project Information Requirements (PIR), usually derived from the OIR, AIR and project specific requirements and supported by ISO 21500 specifications, focuses on specific information needs for successfully develop and implement the project. PIR and AIR are further refined into Exchange Information Requirements (EIR), which establish the precise data exchanges needed during project execution and delivery. The EIR directly informs the development of the Project Information Model (PIM), which consolidates all relevant project data in a structured format for collaboration and decision-making during the project life cycle.

The workflow is designed to improve infrastructure management by enhancing collaboration, streamlining information exchange, and ensuring that all data collected and managed throughout the lifecycle of an asset is precise, relevant, and actionable. A BIM-enabled approach integrates a range of focus areas, each addressing critical aspects of bridge rehabilitation, to transform traditional methods into a more informed and efficient process. Once the information requirements are clearly stated, the technical process can be easily integrated within the digital workflow aiming to tackle:

- Data Collection and Integration of historical records in terms of existing design documents, maintenance logs, and existing on-site inspection reports.
- Current Condition Assessments through field surveys, non-destructive testing (NDT) and a thorough geometric assessment. Advanced techniques such as laser scanning or photogrammetry [20–27] to capture the bridge's geometric and material properties.
- Environmental Data [28–30] on weathering, corrosion rates, and environmental impacts. Integrating these datasets into a common digital environment, such as a BIM platform, ensures accessibility and consistency, enabling stakeholders to analyse the bridge's condition holistically.
- Information Structuring and Standardization to ensure compatibility and ease of use across software tools and project teams. Implementing Industry Foundation Classes (IFC) [31–33] for data exchange and Information Delivery Specifications (IDS) ensures that all required data is correctly formatted and available at the appropriate project stages. Defining Organizational Information Requirements (OIR) and Asset Information Requirements (AIR) early in the project lifecycle further streamlines data management.
- Model Creation and Simulation [34] to develop a federated model to act as a single source of truth central repository for graphical and non-graphical data, enabling:
 - Visualization for stakeholders to assess bridge's current condition and/or proposed rehabilitation strategies through immersive visualizations.
 - Simulation [35] for structural and fatigue assessment [36], and corrosion propagation to allow engineers to evaluate potential failure modes and test repair scenarios.
 - Collaboration, fostering coordination among architects, engineers, contractors, and regulatory authorities.
 - Rehabilitation Planning and Optimization [37], leveraging the insights gained from the BIM model to optimize:
 - Material Selection to allow evaluation of durability and sustainability of repair materials.
 - Repair Strategies, allowing for the identification of the most efficient and cost-effective methods for strengthening or replacing deteriorated components.
 - Monitoring and Feedback Loops post-rehabilitation [38,39] to maintain an up-to-date (As-Built) Asset Information Model (AIM) and enable monitoring and maintenance. By integrating IoT sensors [2], real-time performance data can be captured and analyzed to inform future rehabilitation projects. This feedback loop ensures continuous improvement of workflows and techniques.
- Legal and Regulatory Considerations, including compliance with transportation regulations, structural codes, and environmental policies to ensure that all interventions meet legal and operational benchmarks.

The BIM for Bridges and Structures initiative, particularly the TPF-5 (372) project [40], provides significant added value for establishing clear and efficient BIM workflows for bridge structures. One high value result is the Bridge Lifecycle Management Overview Map [41] (schematically presented in Figure 4), which highlights the interconnected stages of a bridge’s lifecycle, from initial planning and design through construction, operation, and eventual decommissioning or replacement. This process map emphasizes the importance of aligning information needs with lifecycle phases, fostering better collaboration, decision-making, and project efficiency. The map enables stakeholders to understand how information is generated, exchanged, and utilized at different phases, from visualization and analysis in the design phase, to coordination of fabrication and on-site assembly through data-rich models, in the construction phase and condition monitoring for proactive maintenance in the operational phase.

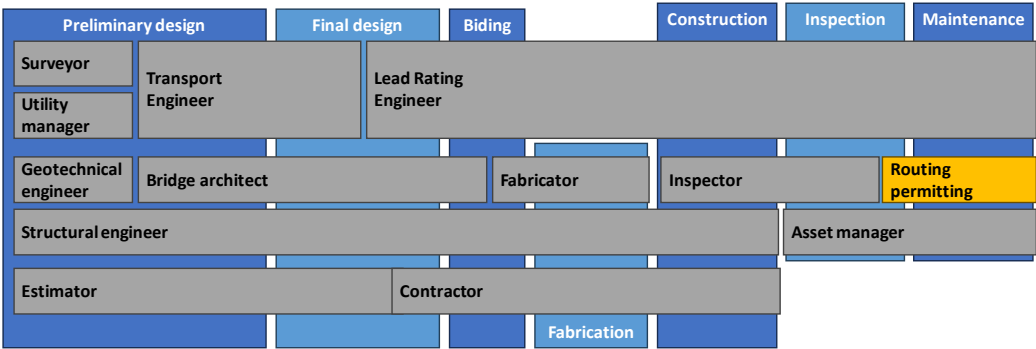


Figure 4. Bridge Lifecycle Management Overview Map.

A strategic plan for collecting, storing, retrieving, and using information is paramount for a successful development of a comprehensive strategy for managing lifecycle asset data across multiple projects. For road infrastructure, the information management process has two main phases i.e., i) development of asset information in the project delivery phase, and ii) the use and updating of asset information in the operational phase [42]. Furthermore, the growing stock of bridges and the increasing need to optimize investments in bridge maintenance, while ensuring safe operation, have created a pressing demand for optimized bridge management [43]. On this line, the “Information Requirements Framework” shown in Figure 3 provides a hierarchical structure that connects the organization’s strategic goals with the detailed information needed for effective decision-making through three distinct but interconnected layers i.e., OIR, AIR, and PIR. Each of these tiers addresses a specific aspect of the broader information ecosystem, ensuring alignment between high-level objectives and on-the-ground project execution.

The templates and guidance developed by the Centre for Digital Built Britain (CDBB) [44–46] provide a robust foundation for implementing best practices in BIM and information management. These resources are particularly valuable for aligning project workflows with the ISO 19650 standards, which focus on structuring and delivering information across the lifecycle of built assets. For projects like heritage bridge rehabilitation, these templates are especially useful, emphasizing trust, value creation, and digital accountability, making them ideal for managing complex projects with historical significance. They also cater to interoperability, facilitate smooth data exchange between different software platforms and ensure compliance with regulatory and sustainability goals. The following sections, offer a brief view of OIR, AIR and PIR for the case of heritage steel bridges.

3.1. The Organizational Information Requirements

This document focuses on the strategic needs of the organization, defining the information necessary to achieve long-term objectives. This includes supporting portfolio-level decision-making, optimizing resource allocation, and addressing compliance with regulatory and sustainability standards. A robust OIR ensures that an organization’s vision, mission, and values are reflected in its

asset management strategy while addressing the specific information needs across all operational phases.

This alignment is particularly vital for structures like the heritage bridges, which combine historical significance with contemporary engineering challenges. From initial planning to the operational phase, the integration of information requirements serves as the backbone of strategic decision-making, ensuring that maintenance, rehabilitation, and eventual replacement are handled efficiently and sustainably.

The OIR document shall detail the following aspects:

- organization's vision and mission that inform its objectives and drive the creation of structured workflows to handle information management (requirements, creation, exchange, storage, use);
- organizational structure and RACI matrix should demonstrate how clear roles and responsibilities enhance collaboration and accountability.
- asset portfolio planning (e.g., exploitation, maintenance, space utilization, and portfolio adjustments) supported by a comprehensive a roadmap for tailored asset management.
- assessment of lifecycle costs, risk assessments, and approaches to rehabilitation, replacement and/or decommissioning.
- environmental considerations, sustainability, and investments, emphasized as key components of a holistic approach.
- information exchange strategy across the organization, including relevant policies, internal and external factors, and implementation plans.
- continuous evaluation and review, to ensure that information remains accessible, consistent, and actionable, to form the foundation for informed decision-making and long-term organizational success.

3.2. *The Asset Information Requirements*

A recurring theme is the challenges in capturing, storing and validating data across a diverse and complex asset portfolio. The AIR document shifts the focus from organization to individual assets, specifying the information needed for their operation, maintenance, and management throughout their lifecycle. It addresses aspects such as inspection data, performance metrics, and maintenance schedules, ensuring that assets like steel bridges are managed effectively, whether they require rehabilitation, repurposing, or eventual replacement.

James Heaton et al. [47] proposed a 7-step process to support the development of information requirements, process summarized hereafter:

1. Identify, Extract, and Categorize Organizational Requirements to ensure that the AIR aligns with the strategic objectives of the organization.
2. Develop Asset Functions, Systems, and Products Within a Classification System to create a standardized understanding of how assets contribute to organizational functions, aiding in effective information management and interoperability.
3. Identify Organizational Information Requirements (OIR) that directly supports the organizational goals and processes identified in Step 1. The OIR should align seamlessly with the previously categorized requirements to ensure the relevance and utility of the information.
4. Develop Functional Information Requirements by translating the OIR into specific functional requirements. This step involves detailing the type of information needed for various operational, maintenance, and management functions, ensuring that all stakeholders have the data they require for decision-making.
5. Develop Asset Information Requirements (AIR) using the functional information requirements as a basis. It should outline what data should be collected, how it should be formatted, and the processes for its maintenance throughout the asset's lifecycle.
6. Validate the Developed Information Requirements to confirm its fitness for purpose. This includes checking its completeness, alignment with organizational needs, and practicality for implementation. If the AIR is not adequate, review and refine it by revisiting earlier steps.
7. Document and Communicate the Developed Information Requirements in a clear and accessible format to all relevant stakeholders, ensuring that the requirements are clearly understood and then integrated into the organizational workflows.

This process emphasizes continuous improvement and alignment with organizational goals, ensuring the information requirements evolve with changing organizational needs. Key milestones like validation and feedback loops, maintain a focus on quality and relevance.

The AIR document should address the following key areas:

- Alignment with Organizational Goals, connecting the broader organizational strategy outlined in the OIR, including the organization's commitment to preserving cultural heritage, sustainability, and efficient resource utilization, especially in the context of heritage steel bridges.
- Asset Inventory and Maintainable Components for all maintainable components, including unique identifiers for structural elements like trusses, beams, and rivets. For heritage assets, the inventory must also capture decorative and historically significant features.
- Lifecycle Management, specifying the requirements for inspection, rehabilitation, and replacement schedules, supported by detailed lifecycle cost analyses and risk assessments. Strategies for extending the lifespan of the asset while preserving its historical and structural integrity should also be included.
- Environmental and Sustainability Considerations on materials and techniques for rehabilitation. Data on the environmental impact of interventions, including carbon footprint and resource efficiency, should be considered.
- Operational Efficiency and Maintenance Strategies for asset performance monitoring, including the integration of IoT sensors to capture real-time data on stress, vibration, and temperature. This ensures proactive maintenance and long-term operational efficiency.
- Data Standards and Classifications, such as Industry Foundation Classes (IFC), to ensure compatibility across BIM tools and platforms. Specific classifications for heritage elements must be included, ensuring accessibility and consistency in information exchange.
- Data Exchange and Integration Protocols providing comprehensive guidelines for information exchange, storage, and access. This includes specifying data formats (e.g., IFC4, JSON) and ensuring interoperability with organizational systems and external stakeholders.
- Validation and Quality Control Metrics for data validation, including model checking tools (e.g., Solibri, Navisworks) and/or rule-based scripts. Metrics for completeness, accuracy, and adherence to preservation standards are essential for maintaining asset quality.
- Continuous Review and Improvement, emphasizing the need for ongoing evaluation to adapt to changing organizational needs and technological advancements. This ensures that the information remains relevant and supports informed decision-making throughout the asset lifecycle.

3.3. The Project Information Requirements

This document focuses on detailed information required for the successful development, implementation, and delivery of the project. This includes detailed data on design, construction, and commissioning, as well as documentation of decisions made during the project lifecycle. Aligned with ISO 19650, the PIR content bridges the gap between the strategic OIR and the asset-specific AIR, ensuring that project-level activities align with organizational and asset management goals. The document development is typically a collaborative effort, often requiring the expertise of a consultancy construction company. In specific cases, the lead appointed party (such as the main contractor) can also support the development. These collaborations play a crucial role in helping the appointing party (i.e., client organization or the operator) identify and articulate the critical information needed at each stage of the project. Their support ensures that the information requirements are practical, achievable, and aligned with both organizational objectives and the data related to project delivery. To achieve this, several types of information needs must be addressed and agreed upon collaboratively:

- Concept phase information needs, such as feasibility studies, preliminary design documents, and sustainability considerations. Clear protocols for information exchange at this stage—particularly between the client and design teams—must also be established, including formats, classifications, and delivery deadlines;

- Detailed design phase requirements, outlining the information necessary to develop a detailed design that addresses technical, regulatory, and operational criteria, like: geometric and performance data for models and drawings, material specifications and engineering calculations, documentation on safety and constructability reviews. The lead appointed party shall ensure that data formatting adheres to recognized standards (e.g., Industry Foundation Classes - IFC) to enable seamless integration into the project's BIM environment.
- Construction phase needs accounting for construction sequencing and scheduling data, inspection and testing plans, records of materials and equipment used, daily reports and deviations from the design. The information exchange protocol for this phase is critical, ensuring that the contractor's data can be efficiently integrated into the federated model and ultimately the Project Information Model (PIM).
- Commissioning and handover phase information specifying the deliverables required to transition the project into operation. This includes the as-built models and drawings, operation and maintenance (O&M) manuals, warranty documents and certificates, digital data for IoT sensor integration, if applicable. The lead appointed party ensures that all information is delivered in formats compatible with the asset management systems defined in the AIR.
- Operation and maintenance phase data to ensure continuity post-handover, the PIR must include guidelines for ongoing information exchange between the project delivery team and asset managers. This encompasses regular updates to the AIM based on PIM data, performance monitoring data, and feedback loops for future asset interventions.

3.4. The Information Delivery Specification

Following the development of the OIR, AIR, and PIR, the creation of a technical document, called Information Delivery Specification (IDS) is usually recommended, as it ensures seamless integration of information requirements into practical workflows. The IDS serves as a technical document that translates natural language, unstructured information requirements into actionable specifications for information exchanges. It bridges the gap between strategic requirements and technical implementation, ensuring that data delivered aligns precisely with the expectations set out in the OIR, AIR, and PIR. Technically, the IDS [48] is a standard development by buildingSMART for defining information requirements in a way that is easily read by humans and can be directly interpreted by computers. It defines the structure, format, and level of detail required for each information exchange, promoting consistency and interoperability across teams and software platforms. It outlines clear rules for data quality, validation, and delivery milestones, facilitating smooth transitions between project phases and ensuring compliance with standards like ISO 19650. IDS is particularly critical for managing BIM workflows, as it provides clarity on how the information should be produced, shared, and utilized. Moreover, the IDS mitigates risks associated with incomplete or inaccurate data, which can lead to inefficiencies, cost overruns, and delays.

An important scope of IDS is that it focuses only on 'information delivery specifications', meaning that it can define what information is needed and how it should be structured. The use of XML (Extensible Markup Language) ensures that these specifications are encoded in a standardized, machine-readable format, providing a versatile framework for defining structured data. This standardization is critical for aligning the IDS requirements with industry standards like IFC (as given by ISO 16739-1:2024) in openBIM workflows. By leveraging XML, IDS can define what information is required together with the format, classification, and validation rules that ensure data interoperability across various BIM platforms. It also allows for the validation automatization. It must be mentioned that IDS has been identified by the international community as the most advantageous method for automated compliance checking by validation of alphanumerical information requirements. Extensive technical information related to IDS can be found on GitHub [49], where code development, documentation, and examples are kept.

4. Case Study for the Săvârșin Heritage Steel Bridge

The case study presented hereafter is focused on the Săvârșin heritage steel bridge (see Figure 5), a historical structure located in Romania, crossing the Mures River on the local DJ 707 road. The

bridge, constructed in 1895, embodies the classical structural design characteristic of its era. Its primary load-bearing elements are parabolic lattice beams, featuring descending diagonals (in tension) and vertical struts (in compression). Spanning 159.2 meters, the bridge consists of four simply supported truss girders, each measuring 39.8 meters, with a length-to-height ratio of 1/6.4 (39.6 meters/6.22 meters). The main beams give the bridge a graceful and harmonious appearance, perfectly integrating into the picturesque landscape near the former summer residence of Romania’s royal family. The bridge’s stability is enhanced by a transversal bracing system located in the four central panels at the top of the longitudinal beams. Its load-bearing track structure comprises an orthogonal network of stringers and struts supported by Zores profiles. Above this framework lies a 20 cm ballast layer, topped with a 5 cm layer of asphalt concrete, forming the final roadway surface. As a riveted structure, construction method widely used in the past but less common today, the bridge holds significant historical value, adding further complexity to its maintenance. This combination of historical design and technical sophistication underscores its importance as an engineering marvel and also as a cultural landmark.

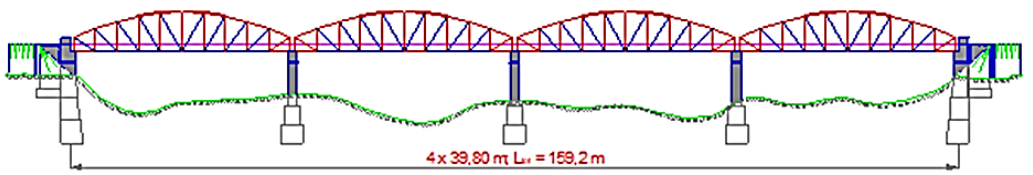


Figure 1. The overview of the Săvârșin bridge.

As a testament to the engineering ingenuity and architectural sophistication of its era, the Săvârșin Bridge is not only a vital piece of infrastructure but also a cherished landmark, having an emblematic value for the local community. Its enduring legacy reflects the balance of modern preservation techniques and the cultural importance of maintaining such historical structures. Despite comprehensive rehabilitation efforts completed in 2008, the bridge remains in a state of partial disrepair, necessitating ongoing maintenance to safeguard its historical significance [50].

The bridge rehabilitation stands as a remarkable achievement, exemplifying excellence in preserving heritage while ensuring structural integrity. Recognized by the European Convention for Constructional Steelwork (ECCS), the project received a prestigious award that highlighted its success in addressing both engineering and architectural challenges. Further acclaim came in 2010, when the bridge was honoured with the European Prize for Rehabilitation of Bridges, underscoring the project’s innovative approach to strengthening all structural elements through both direct and indirect methods.

4.1. The OIR, AIR and PIR Documents

As shown before, the effective information management throughout the rehabilitation of heritage steel bridges, like the Săvârșin Bridge, require a well-defined hierarchy of information requirements to ensure that organization’s strategic goals are aligned with the operational and project-specific needs necessary to preserve the bridge’s historical, structural, and functional integrity. Public authorities managing infrastructure (i.e., roads, bridges, and/or buildings) can use the principles outlined in UNECE guidance [51] on asset management and BIM to derive a structured set of information requirements. Table 1 provides a proposal for information requirements at the organizational, asset and project level, as they relate to the Săvârșin Bridge. The information provided within the table accounts on how each requirement contributes to a cohesive and efficient information flow for managing future rehabilitation efforts and ongoing operation of such significant assets.

The OIR ensure that public authorities are receiving information that equip them to manage infrastructure assets effectively, emphasizing sustainability, resilience, and technology integration. Next, the AIR considers efficient decision-making throughout the lifecycle of the bridge, ensuring both its structural functionality and integrity, while preserving its cultural significance. The PIR

ensures that the project progresses efficiently, within time and budget constraints, and meets long-term objectives for heritage preservation and infrastructure functionality.

These requirements ensure that public authorities are equipped to manage infrastructure assets effectively, emphasizing sustainability, resilience, and technology integration.

Table 1. Sample information requirements for heritage steel bridges.

Organizational Information Requirements (OIR)	Asset Information Requirements (AIR)	Project Information Requirements (PIR)
- Enhance safety, ensuring sustainability, improving lifecycle management, and promoting resilience against climate change. - Ensure compliance with international standards and national regulations for data, project and asset management. - accurate documentation of all assets, including their location, condition, and performance metrics. - Enforce protocols for data collection, validation, and sharing across departments and stakeholders to ensure seamless operations. - Define requirements for information that supports lifecycle cost analysis, helping to assess maintenance, operation, and eventual decommissioning costs. - Consolidate structural integrity, vulnerabilities, and risk mitigation plans, especially for heritage structures like steel bridges. - Detailed data on energy usage, emissions, and environmental impacts associated with infrastructure projects. - Data integration with environmental monitoring tools to assess compliance with sustainability goals. - Foster transparency through public dashboards or reports on infrastructure conditions and projects.	- Historical and current inspection reports, including photographs, defect mapping, and condition ratings. - Maximum allowable loads and records of any modifications to structural elements that could impact load distribution. - Detailed information of steel composition, coatings, and any corrosion-resistant treatments available. - High-resolution 3D scans to capture the exact geometry of the bridge, including deformations or irregularities caused by aging. - GIS-integrated spatial data to ensure proper alignment with surrounding roads, railways, and waterways - Records of all maintenance activities, including the date, type of intervention (e.g., painting, rust removal), and costs. - Documentation of all repairs, retrofitting, or strengthening actions taken to preserve the bridge. - Detailed records of original design elements, such as lattice patterns, rivets, or decorative features, to guide any restorative actions. - Information on the historical importance of the bridge and guidelines for maintaining its heritage value during rehabilitation. - Data on the impact of the bridge on local ecosystems, especially for projects	Project Development - Heritage-specific constraints and restoration objectives, to ensure project’s alignment with cultural and structural preservation standards. - Detailed data requirements for baseline assessments, including material degradation, structural vulnerabilities, and environmental impact studies. - Information exchange protocols for engaging historians, engineers, and local authorities to ensure that all parties align on the project’s vision. - High-resolution 3D scans and initial condition assessments to create a detailed BIM model. - Financial information that incorporate lifecycle costs and heritage conservation expenses. - Rehabilitation information related to activities that affect local ecosystems, with mitigation strategies. Implementation - Requirements for updating BIM models with real-time progress data from construction activities, including retrofitting of structural elements. - Data submission protocols to demonstrate adherence to national engineering and heritage preservation standards.

- Data integration to support digital twin models to simulate and manage infrastructure assets effectively	involving watercourses or urban areas. - Information on embodied carbon in steel and measures to reduce emissions during maintenance activities. - Data requirements for integrating IoT sensors to monitor vibrations, stress levels, and environmental conditions such as humidity and temperature. - Data on potential hazards, including natural disasters, and mitigation plans for preserving structural and heritage integrity. - Ensure all data formats are interoperable with existing systems used by the public authority managing the asset.	- Data from IoT sensors installed on the bridge to monitor stress, temperature, and vibration during rehabilitation works. Handover - Deliver a fully updated as-built model of the bridge, including all modifications, material updates, and remaining vulnerabilities. - Detailed records of final inspections, structural load testing, and certifications from regulatory authorities. - Schedules and procedures for ongoing and future inspections and minor restorations based on asset information. - Provide technical training for local authorities and maintenance teams on using the BIM system and interpreting sensor data. - Deliver manuals that include heritage-specific maintenance strategies to guide future interventions.
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4.2. The IDS File

Based on these documents, the IDS shall outline the data requirements for specific tasks and/or phases in within the BIM workflow and ensure that all project stakeholders provide and manage information in a standardized, efficient manner.

A natural language IDS example for Heritage Steel Bridge Rehabilitation is presented hereafter.

General Information

- Project ID: SAV-HB-2024;
- Phase: Development, Implementation, Handover;
- BIM related standards: ISO 19650-1:2019, ISO 19650-2:2018, ISO 16739-1:2024, ISO 7817-1:2024.

Data Exchange Requirements

- File formats
 - IFC4 for interoperability
 - Native file formats for design tools (e.g., Revit, Tekla Structures, Bonsai, etc.).
 - CSV or JSON for IoT sensor data.
- Software Compatibility: Must be compatible with common BIM tools and platforms such as Navisworks, BIM 360, and open-source tools adhering to buildingSMART standards

Information Requirements by Phase

- Development Phase
 - Structural Assessments:
- Input:** 3D scans (point cloud in .e57 format), initial condition reports (XML).

- Output:** Preliminary BIM model with structural analysis data.
- Environmental Impact:
Input: GIS data (.shp files) and climate analysis reports.
Output: Environmental risk assessments incorporated into the BIM model.
- Implementation Phase
 - Construction Data:
Input: Specifications for retrofitting materials (steel grades, paint types, rivets).
Output: Updated BIM model showing real-time construction progress (weeekly .ifc updates).
 - Monitoring Integration:
Input: IoT sensor placement data (JSON).
Output: Integration into a digital twin for real-time monitoring.
 - Handover Phase
 - As-Built Documentation:
Input: Final scans and updated design data.
Output: Comprehensive as-built BIM model with maintenance schedules embedded.
 - Training Materials:
Input: Operation manuals, sensor data management protocols.
Output: Interactive digital guides linked to the BIM model.
- Data Validation and Quality Control**
- Validation Tools
 - Model checking tools (e.g., Solibri, Navisworks).
 - Custom scripts for rule-based validation (e.g., Python scripts).
 - Quality Control Metrics
 - Completeness (percentage of mandatory fields populated).
 - Accuracy (validation against reference standards e.g., ISO 1090-1, ISO 1090-2).
- Governance and Access Control**
- Access Levels
 - Read-only for public authorities.
 - Edit access for BIM managers and contractors.
 - Audit Trail
 - Maintain version history of the BIM model and associated documents.

Complementing the IDS framework described before and enable the development of a XML based IDS, Table 2 outlines specific data fields and their requirements, tailored for the case of rehabilitation of heritage steel bridges.

Table 2. Sample data fields for the IDS.

Field	Requirement	Format	Phase
Structural Element ID	Unique identifier for each component (e.g., beams).	String (UUID)	Development
Material Properties	Steel composition, corrosion resistance.	JSON, XML	Development
Geometric Data	Dimensions, curvature, alignment tolerances.	IFC, .e57	All phases
Heritage Details	Decorative features and original designs.	PDF, linked IFC	Development, Handover
Load Capacity	Maximum weight and stress tests results.	Numeric (kN)	Implementation
IoT Sensor Data	Vibration, stress, temperature readings.	JSON, CSV	Implementation

Based on information requirements, the IDS XML file is developed, with an example presented in Appendix A.

4.3. The Technical Report and Rehabilitation Decision

The BIM workflow creates the structure for the information exchange. The technical component of the rehabilitation process for existing steel bridges involves several key steps that must be carefully analyzed and addressed by technical experts. As discussed in previous sections, the initial step requires on-site assessment of the structure's technical condition, with several key factors to consider, such as identifying whether the bridge is made from wrought iron or mild steel. This distinction is especially important for older bridges, as mild steel became more common after 1900. The technical condition also includes the evaluation of structural damage, particularly to vertical members of the truss girders, often caused by insufficient clearance and vehicle impact. Furthermore, many heritage steel bridges in Romania suffer from insufficient maintenance due to historical ownership changes, which leads to significant corrosion and the absence of proper documentation about their construction and maintenance.

For skewed or curved bridges, or continuous truss girders, advanced 3D space analyses enabled by modern computer-aided engineering (CAE) techniques are necessary to assess the current state they as can offer detailed information. Nevertheless, for older bridges are statically determined structures, that are typically constructed perpendicular to their supports to ensure a uniform and direct load transfer, analytical methods can be employed as they offer sufficient accuracy. These old bridges are generally riveted, and the lack of knowledge regarding material quality presents additional challenges. To mitigate this, the Romanian Highway Administration (CNAIR) has developed a qualitative verification methodology, AND 522-2002 [51], to assess the condition of these structures, providing a categorization based on expert evaluation that informs decisions on repairs or replacement. However, this methodology is effective for newer bridges (less than 30 years old) and serves more as an informational tool for older steel structures, which require a more detailed assessment methodology, as outlined in Figure 2.

Based on the AND 522-2002 [52] specifications, technical condition of the structure is assessed in terms of a quality index given by Eq. 1:

$$I_{ST} = \sum_{i=1}^{i=5} C_i + \sum_{i=1}^{i=5} F_i \quad (1)$$

where the quality index C , accounts for C_1 the main girder; C_2 the deck elements; C_3 the infrastructure and bearings; C_4 the riverbed and C_5 the deck surface quality, while F refers to the functional requirements with F_1 to the traffic conditions on the bridge; F_2 to the loading class of the road; F_3 to the year of construction and type of structure; F_4 to the quality of fabrication, erection and operation; F_5 to the maintenance of the structure.

For every index (from 1 to 5), one mark (1 – 10) is awarded. Finally, the technical condition of the structure results from the total sum and can be ranged in one of the following categories:

- Very good technical condition;
- Good technical condition;
- Satisfactory technical condition;
- Unsatisfactory technical condition;
- The present technical condition cannot assure the safety of the structure.

For the time being, the Săvârșin bridge was evaluated using a classical simplified analysis. The general stability of the compressed upper chord of the main girder was checked, while the computed structural stresses for the considered load cases exceed the allowable values by 10 – 40%, for specific structural elements.

A more complex problem is posed by the fatigue assessment. To estimate the fatigue effects, the damage accumulation methodology (usually applied for railway bridges) was employed, even if for usual road bridges this verification was not foreseen by the Romanian code [53] at the time. To implement the procedure, an adaptation of the Wöhler curve can be utilized, following the

assumptions outlined in the Swiss Railways specification [54] for existing bridges, as illustrated in Figure 6.

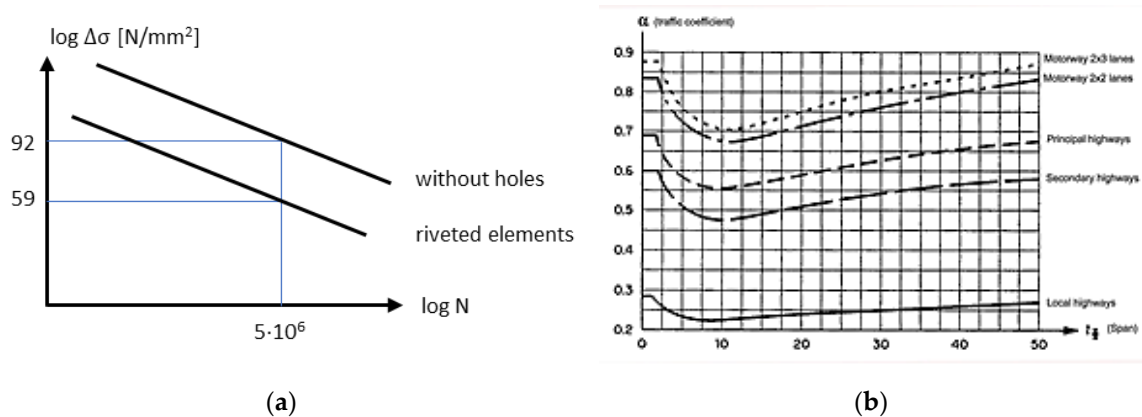


Figure 6. Wöhler Curve and Traffic coefficients for highway bridges the Swiss Regulation.

Reliable fatigue life predictions for bridges heavily depend on accurate traffic data collected over the bridge's life span. Furthermore, evaluating the actual stress history of a structure presents significant challenges, as factors like the detailed geometry of the bridge and the number of stress cycles experienced greatly influence its remaining fatigue life. In usual engineering applications, it is often necessary to assume that the traffic load spectrum remains consistent throughout the bridge's lifespan or, at least, during specific discrete periods. By analysing this stress history in conjunction with the appropriate Wöhler curve, specialists can estimate the accumulated damage, assess the bridge's fatigue performance and give an informed estimation its remaining service life.

For example, in the case of the main girder – lower chord (middle span) the verification is the following:

$$\Delta \sigma = 73.5 \text{ N/mm}^2$$

$\alpha = 0.57$ for secondary highways (see Figure 6b)

$$\Delta \sigma_e = 0.57 \cdot 73.5 = 41.9 \text{ N/mm}^2 < \frac{80}{1.1} = 72.7 \text{ N/mm}^2$$

Considering the importance of the structure, its historical value, and the aesthetic appearance (see Figure 7) the decision of strengthening of the structure was taken.



Figure 7. The general view of the Săvârșin bridge.

Most of structural elements were assessed and reinforced and presented hereafter:

- the stringers the flanges were consolidated by supplementary plates (see Figure 8);

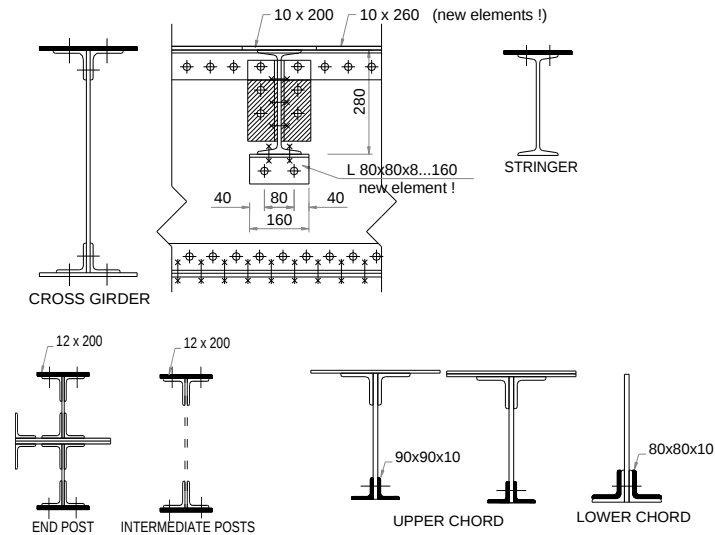


Figure 8. Direct reinforcement with additional elements.

- the cross girders were transformed in switch girders (see Figure 9);

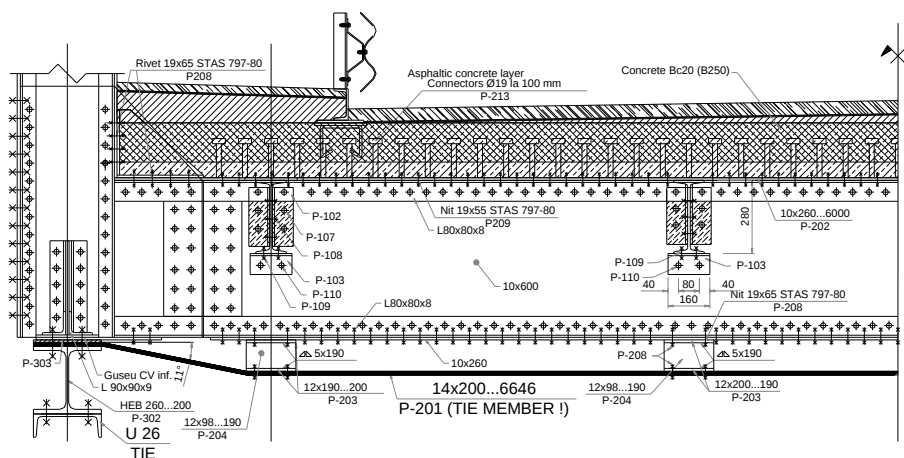


Figure 9. Cross girder reinforcement with a tie member.

- supplementary tie member for the main girder lower chord (see Figure 10);

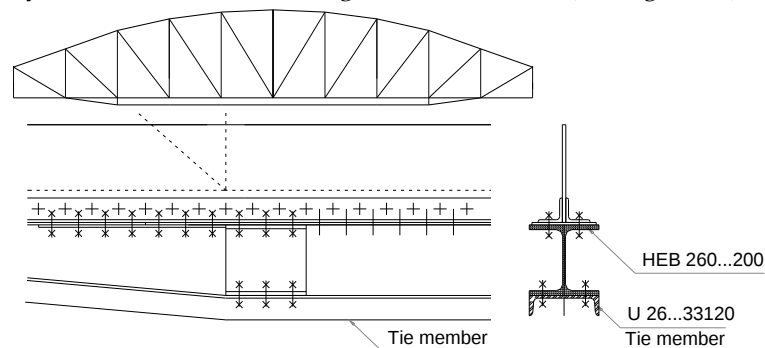


Figure 10. Main girder reinforcement with a tie member.

- the upper chord stability was improved by direct strengthening with two angle profiles (see Figure 11);

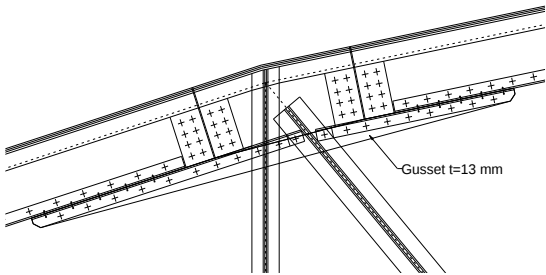


Figure 11. Upper chord stability improvement.

- diagonals and vertical members have to be first of all straighten, and strengthen by additional plates;
- the old deck system was replaced by a composite deck (see Figure 12).

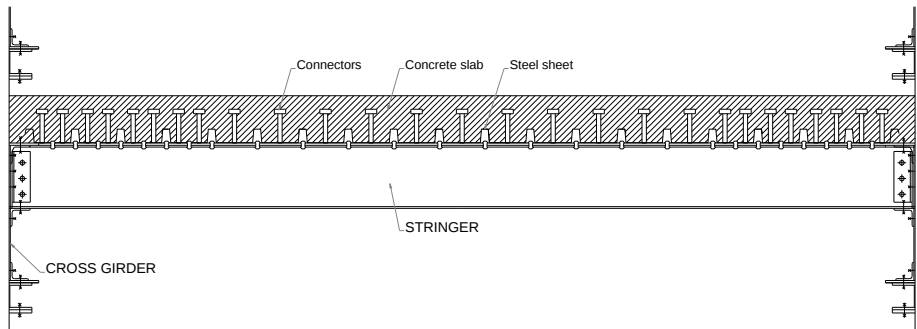


Figure 12. The bridge new composite deck.

All these operations are difficult and suppose a high technical level of all in situ works, with several in situ procedures presented in Figure 13.



(a)



(b)



(c)



(d)



Figure 2. On-site work for bridge rehabilitation: (a) deck removal; (b) Warm post straightening; (c) sand blasting; (d) Riveting; (e) New consolidation elements; (f) Reinforcement of upper chord joint.

5. Concluding Remarks

The adoption of Building Information Modelling (BIM) workflows for the rehabilitation of heritage steel bridges represents a transformative step for national authorities, as custodians of extensive infrastructure networks. BIM's ability to centralize and manage data throughout an asset's lifecycle, offers unparalleled advantages in ensuring the longevity and functionality of these critical structures. It enables informed decision-making processes, allowing infrastructure owners to optimize rehabilitation strategies, efficiently allocating resources, and prioritizing interventions based on accurate, real-time data. Furthermore, the potential to integrate BIM data into Digital Twins can create significant opportunities for enhanced operation and maintenance planning, providing a dynamic representation of assets, enabling predictive analysis and condition-based monitoring, thus improving the overall resilience and sustainability of infrastructure networks. Additionally, the BIM enabled structured approach to information management, allows for consolidation of all bridge-related data into a centralized repository, allowing stakeholders to access up-to-date records for each specific asset.

It must be noted that currently, the BIM process and the technical assessment and rehabilitation process operate independently, while they should be complementing each another. Consolidating the information about the current condition of assets, with the comprehensive records of past interventions, and ongoing performance monitoring, can provide a robust foundation for future interventions. This approach would facilitate the development of time-dependent simulations, enabling authorities to evaluate the potential impact of various strategies, while allowing stakeholders to layer intervention data and create a chronological map of an asset's evolution. This synergy fosters a more proactive and sustainable approach to infrastructure management, supporting the dual goals of preserving cultural heritage and maintaining functional road networks for future generations.

BIM enabled digital processes creates multiple opportunities for managing heritage steel bridges, empowering national authorities to transition from reactive to proactive asset management and setting a new standard for the rehabilitation and preservation of transportation infrastructure, while considering the sustainable goals.

Author Contributions: Conceptualization, A.C. and R.B.; methodology, A.C.; formal analysis, A.J.; investigation, A.J.; resources, A.C.; data curation, A.J.; writing—original draft preparation, A.C.; A.J.; writing—review and editing, A.C.; visualization, A.C.; supervision, R.B.; project administration, R.B.; All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

This sample document, illustrates a practical implementation of an Information Delivery Specification (IDS) tailored for the rehabilitation of a heritage steel bridge presented in XML

(Extensible Markup Language) format. It is structured to reflect the key phases of the project lifecycle i.e., Development, Implementation, and Handover and aligns with established industry standards, including ISO 19650 and IFC4. Each phase outlines specific information requirements, detailing the type of data needed, its format, the source of the information, and the responsible verifier.

The IDS is intended to integrate robust data validation mechanisms, specifying tools and metrics to ensure accuracy, completeness, and compliance with regulatory and project-specific standards. Governance elements, such as access control and audit trails, are included to ensure transparency and accountability throughout the project.

This example is intended to demonstrate how an XML-based IDS facilitates seamless communication among stakeholders, enhances data reliability, and supports informed decision-making.

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    <ProjectName>Săvârșin Heritage Bridge Rehabilitation</ProjectName>
    <Version>1.0</Version>
    <CreatedBy>Structural Engineers Inc.</CreatedBy>
    <DateCreated>2024-12-11</DateCreated>
  </GeneralInformation>

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        <Verifier>Load Testing Engineer</Verifier>
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</Validation>

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    <Role name="BIM Managers" accessLevel="Full Access" />
  </AccessControl>
  <AuditTrail>
    <Enabled>true</Enabled>
    <Description>Track changes to all project data and models.</Description>
  </AuditTrail>

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</AuditTrail>
 </Governance>
 </IDS>

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