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WELDED STEEL BRIDGE INTEGRITY ENABLED BY SMART INFORMATION MANAGEMENT ACROSS THE ASSET LIFECYCLE

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Abstract: *This paper presents a BIM-enabled framework for improving decision-making, quality control, and asset management applied to steel bridges. By integrating information management throughout the asset lifecycle, non-destructive testing, and predictive maintenance concepts, it addresses challenges like fatigue failure and material degradation considered linked to execution class. A key contribution is the "backward standard correlation" approach, that ensures integration of operational needs in design, aiming to optimize procurement and reduce lead times, while enhancing overall lifecycle cost efficiency. The proposed BIM-based approach enables real-time monitoring, stakeholder collaboration, and structured data exchange within a Common Data Environment. The proposed approach supports Industry 5.0 principles, by advancing digitalization, enhancing design and execution practices, while offering a solution for long-term performance monitoring.*

Keywords: *Building Information Modeling (BIM), Digital Manufacturing, Welded Steel Bridges, Execution Class, Non-Destructive Testing (NDT), Fatigue Damage Assessment*

1. INTRODUCTION

The importance of welded metal bridges in modern transport infrastructure lies in their durability and adaptability to different loads and site conditions. However, ensuring their long-term structural integrity poses significant challenges. Fatigue-induced failure, corrosion, and welding defects are major concerns that compromise the life of these structures. Predictive maintenance considerations and the need to assess structural damage over time is often disregarded during design phases, resulting in expensive repairs and unexpected failures. Furthermore, as the design of modern bridges is becoming more complex, their design, construction, and operation require advanced methods that incorporate real-time monitoring, predictive analysis, and advanced quality control. On this line, compliance with SR EN 1993-1-9 [1] and SR EN 1090-2 [2] is crucial for ensuring structural reliability and safety. From the structural point of view, within the Eurocode standard package, safety principles are guided by interconnected requirements that influence the entire construction process, from product quality to design, execution, and assembly.

By consistently implementing a strict safety concept related to various materials, structural types, and actions (e.g., concrete, wood, foundations, and seismic actions), the probabilistic approach within Eurocode guarantees a design lifespan of 100 years. Furthermore, this comprehensive regulatory framework ensures compliance with execution class (EXC3 or EXC4 for bridges) material selection, welding procedures, and quality control measures when building new structures. The revised SR EN 1090-2 [2] introduces even stricter requirements for manufacturing and inspection, further enforcing probabilistic safety concepts to ensure long-term performance. Safety and service life assessments for existing structures must follow specialized rules that are adaptable to the bridge's operational history and current condition.

Using advanced concepts like Digital Twins and Scan-to-BIM, asset owners can structural health monitoring throughout asset lifecycle, construction planning and accuracy. Moreover, BIM-based predictive maintenance improves proactive decision-making, lowering the likelihood of fatigue failure and extending bridge life. Additionally, Non-Destructive testing (NDT) integration within BIM improves fault detection and repair planning while also ensuring quality and safety standards are met throughout the asset's life cycle.

The purpose of this paper is to present a comprehensive framework for integrating digital production and BIM to improve the decision-making process for welded steel bridges by:

- introducing the backwards standard correlation method for choosing materials and execution classes;
- presenting a structural reliability assessment procedure in accordance with SR EN 1090-2:2018 [2] requirements for execution classes (EXC3, EXC4 for bridges);
- highlighting the benefits of BIM-based approaches for predictive maintenance and life cycle cost optimization.

2. APPLICATION FIELD

2.1 Welded bridge design, construction and maintenance challenges

The design, construction and maintenance of steel-welded bridges is a complex process that involves multiple stakeholders, various disciplines and presents numerous challenges, that includes:

- fracture risks due to fatigue-induced weld cracking caused by cyclic load, which can lead to structural failure if not properly managed.
- accelerated material degradation caused by prolonged environmental exposure, requiring protective coating and regular inspections to maintain the desired performance level.
- a complex life cycle management given that traditional maintenance is based on reactive strategies, often leading to expensive interventions and unplanned repairs.
- complex interdisciplinary coordination for effective design, construction and operation, that requires seamless collaboration between designers, fabricators, contractors, and asset managers to ensure compliance with standards and structural performance.
- complex quality control in fabrication and execution to ensure compliance with SR EN 1090-2 [2] demands for rigorous welding procedures, certified personnel, and NDT.

2.2 Benefits of BIM-enabled asset manage ment

To mitigate the above-mentioned risks, the integration of BIM workflows and digital manufacturing within project development, organizations can revolutionize bridge lifecycle management, offering multiple benefits, like:

- enhanced design accuracy, by enabling parametric modeling and early clash detection, improving constructability and reducing rework costs;
- optimized execution planning, ensuring high-precision fabrication and real-time monitoring of welding quality , including the NDT results;
- improved asset monitoring through BIM-based predictive analytics, enabling proactive maintenance strategies;
- streamlined stakeholder communication based on centralized digital models that ensure real-time access to design, execution, and operational data;
- streamlined regulatory compliance, ensuring that all phases—from design to maintenance—comply with Eurocode 3 [1], SR EN 1090-2 [2] and probabilistic safety concepts, supporting a 100-year design life.

3. STANDARD CORRELATION

3.1 Forward standard correlation: information flow from design to operation

The development of a welded steel bridge project follows a structured sequence, beginning with design, continuing through manufacturing, construction, and ultimately operation and maintenance. At each stage, compliance with Eurocode and SR EN 1090-2 [2] ensures quality and durability, with a focus on achieving a service life of 100 years.

During the design phase, engineers define the structural integrity requirements and performance criteria based on expected loads, environmental factors, and safety considerations. The execution class (EXC3 to

EXC4) is determined according to the bridge's function and complexity, while material selection and fabrication tolerances are specified in alignment with Eurocode and SR EN 1090-2 [2] specifications.

Once the design is completed, manufacturing begins. Factory production control ensures that all components meet their design specifications. Fabrication acceptance tests (FAT) are performed to ensure that the weld quality, component alignment, and material properties meet the required standards for each element. The welding process itself must adhere to SR EN 1090-2 [2], particularly for upper execution classes (i.e., EXC3 and EXC4), which have stricter quality control requirements.

After manufacturing, the components move into the assembly and construction phase. Visual testing (VT) is carried out prior to installation to ensure that the elements meet all quality standards. In specific chases, NDT is carried out in accordance with SR EN 1090-2 [2] to detect any defects that are not visible to the naked eye. Strict quality control procedures are followed during installation to ensure the structural integrity promised during the design phase.

Finally, during the service and maintenance phase, the structure is subjected to routine inspections and fatigue assessments using various techniques [3]. Predictive maintenance strategies could employ BIM technologies [4], [5], which enable real-time monitoring and optimization of inspection and repair programs. Structural health monitoring (SHM) should be employed to ensure that the bridge meets long-term safety and sustainability standards.

Figure 1 illustrates the forward standard correlation process followed by most projects.

While this method ensures compliance with established design and execution standards, it often neglects decisive practical considerations. Specifically, it does not account for the actual capabilities and production limitations of manufacturing facilities, nor does it evaluate the feasibility of implementing costly NDT methods. As a result, sourcing suitable suppliers can become extremely complex and expensive, leading to longer lead times and potential project delays. Additionally, it does not integrate the client's operational requirements, such as budget constraints for inspections, the limited capacity and/or capability during the bridge's service life.

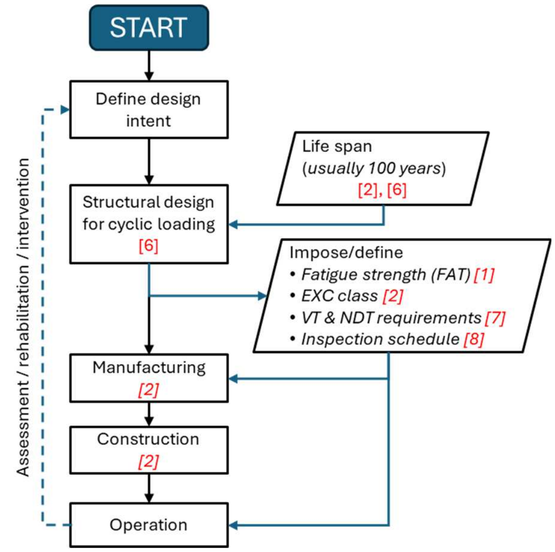

Fig. 1. Forward standard correlation.

On this line, by prioritizing theoretical compliance over practical execution and long-term maintainability, this approach may inadvertently result in inefficient and costly outcomes.

3.2 Backward standard correlation: requirements flow from operation to design

While the construction process follows logical progression from design to operation, the requirements for ensuring long-term performance must flow in the opposite direction. This backward correlation ensures that real-world conditions influence the decisions made at the earliest stages of a bridge's development.

During the operational phase, the bridge must withstand fatigue, corrosion and other environmental effects over its intended 100-year lifespan. Regular inspections and, sometimes NDT dictate the quality control measures that need should be established during fabrication and assembly. These operational considerations set the foundation for construction requirements.

During the construction and assembly phase, the considered execution classes define the necessary tolerances for fabrication, the quality of welding, and the extent of material testing. The results of VT and NDT to be conducted during this stage help establish the minimum quality requirements that manufacturing processes must meet. On the other hand, manufacturing must ensure that welded joints and materials can endure long-term operational stresses. FAT serves as a checkpoint, verifying compliance with the necessary standards before components are transported and assembled on-site. Ultimately, all these requirements should influence the initial design phase. The safety framework established by Eurocode, along with its probabilistic assessments, ensures that bridges are designed to withstand real-world operational conditions. The integration of digital manufacturing and BIM enables data-driven decision-making, improving efficiency, durability, and resilience. By considering operational requirements from the project outset, designers can anticipate future maintenance needs, ensuring optimal performance throughout the bridge's lifespan.

The backward standard correlation, presented schematically in Figure 2, represents a shift from the traditional workflow to a more integrated and collaborative process, where the client, owner, and/or operator actively engages with designers, manufacturers, and constructors from the project outset. This early alignment ensures that all stakeholders agree on key aspects such as production capabilities, quality control measures, the feasibility of VT and NDT, as well as long-term inspection and maintenance strategies.

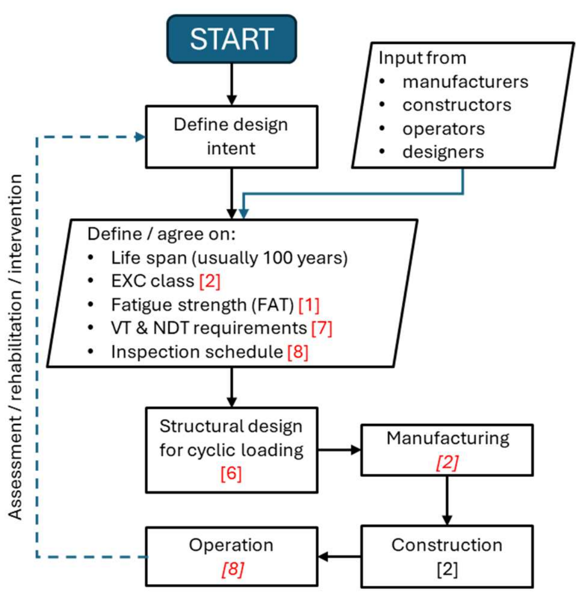

Fig. 2. Backward standard correlation (adapted from the International Welder course [12]).

While this adjustment may seem minor in the early stages of the project, it has profound implications for project implementation, as it enables procurement optimization, can reduces lead times, and enhance cost efficiency by ensuring that design and execution decisions are both realistic and aligned with operational constraints.

A key blocking point for implementing this approach is represented by legal and contractual limitations, as many infrastructure projects follow rigid procurement rules that separate design, construction, and operation into distinct contractual phases, limiting the ability to form a unified agreement across all stakeholders. However, by fostering early-stage discussions and balancing project specifications with execution feasibility, this method significantly enhances the overall value of the project.

3.3 Technical requirements for quality assurance

In welded bridge construction, the selection of the execution class is essential for ensuring compliance with safety and durability standards. The correlation between execution class and quality requirements follows the European standards given in Table 1. The safety philosophy of European standards, explicitly given by SR EN 1990 [13] ensures predefined service life expectations for 100 years for monumental structures, bridges, and other major engineering works.

Table 1

Execution class to quality requirements mapping.

Execution class	Quality requirements
EXC1	SR EN ISO 3834-4 "Basic Quality Requirements" [9]
EXC2	SR EN ISO 3834-3 "Standard Quality Requirements" [10]
EXC3 EXC4	SR EN ISO 3834-2 "Comprehensive Quality Requirements" [11]

It must be mentioned that execution class EXC4 is meant for structures where failure would lead to catastrophic consequences, including loss of life, environmental damage, and/or severe financial loss. The classification and justification of execution class selection fall under the designer's responsibility and shall be an integral part of the project documentation. It is highly recommended that the contractor (i.e., steel assemblies manufacturing facility) formally request confirmation of the execution class during the contracting phase of the project.

Table 24 from SR EN 1090-2 [2] specifies the extent of routine supplementary NDT (i.e., penetrant testing [14], magnetic particle testing [15], ultrasonic testing [16], [17], [18] or radiographic testing [19], [20]).

For EXC1, EXC2 and EXC3, the execution specification may identify requirements for production testing and specific joints for inspection together with the extent of testing. For EXC4, welds, the scope of supplementary NDT shall be specified with respect to each weld. The extent of testing (expressed as percentage of all welds from a specific lot) given by Table 24, aims to ensure quality control by requiring random testing of at least *p*% of each weld's length. If the total weld length in an inspection lot is under 900 mm, at least one weld must be fully tested. For multiple identical short welds, a random selection totaling at least *p*% of the overall length must undergo full testing.

Yet, in some specific cases, these verification limits are insufficient. To limit ambiguity, Annex L, of the same standard introduces Welding Inspection Classes (WIC), detailing the required extent of NDT for each decisive weld. If WICs are to be used, *Table L.1 – Guidance on a method for selection of weld inspection class* and *Table L .2 – Percent extent of supplementary testing according to WIC* from SR EN 1090-2 outlines a systematic approach to their selection, based on:

- utilization for fatigue in structures subject to cyclic loading that require more rigorous inspection to mitigate fatigue-related failures,
- consequence of failure where the structural impact of a weld failure shall determine the necessary level of inspection (e.g., main load-bearing elements in bridges that requires a higher inspection standards.
- direction, type, and level of stresses, where the magnitude and orientation of stresses acting on a welded joint influence its susceptibility to failure, guiding the selection of an appropriate inspection class.

Although Annex L is informative, rather than a mandatory requirement, it serves as a valuable tool for designers in ensuring appropriate weld quality as a failure in welded joints or principal structural elements can have severe consequences, including risk to human life (structures supporting people or positioned above public areas), significant environmental pollution and/or high financial losses.

Conversely, low-risk importance applies to structures designed with robustness principles, ensuring redundancy, and preventing total collapse even if localized overloading occurs. When weld stresses exceed 50% of the joint's load-bearing capacity, additional verification of lamellar tearing susceptibility is required.

Ensuring structural safety and quality is a fundamental aspect of engineering standards. The scope of NDT, as specified in SR EN 1090-2 [2], is critical for maintaining quality control, especially in critical welded joints. However, standard verification limits may sometimes be insufficient, necessitating the use of WICs for a more rigorous, risk-based approach. These factors are critical in fatigue-prone structures, primary load-bearing elements, and joints that are subject to high stress levels.

BIM appears to be a viable framework for effectively implementing these quality control measures and improving project coordination. BIM facilitates seamless collaboration among stakeholders, ensuring that project requirements are aligned from the operational to the design phases and that critical information flows efficiently from design to operation.

4. THE ADDED VALUE OF BUILDING INFORMATION MODELING (BIM)

4.1 BIM definitions and information models

SR EN ISO 19650-1 [21] defines BIM as "the use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions."

For welded bridge design, manufacturing, construction and operation, it can serve as a structured framework to integrate requirements and streamline information flow across all project phases. By providing a central digital environment where project data is continuously updated and shared, BIM ensures alignment between stakeholders, enhancing decision-making throughout the asset lifecycle.

A well-defined requirements management process is essential for a successful BIM strategy. This process, schematically presented in Figure 3, is structured into the following:

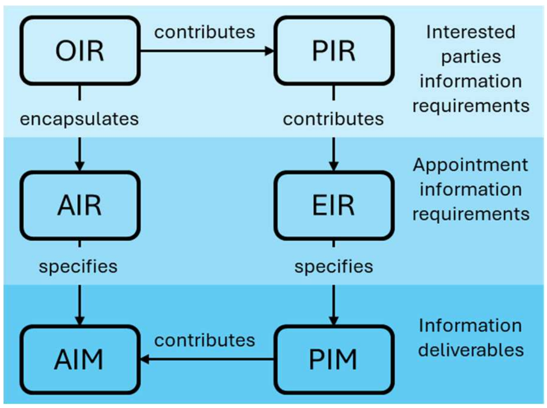

Fig. 3. Hierarchy of information requirements.

- Organizational Information Requirements (OIR) that explain the information needed to answer or inform high-level strategic objectives within the client or asset owner (i.e., appointing party). OIR can support reasons other than asset management (e.g., submitting annual financial accounts).
- Asset Information Requirements (AIR) set out managerial, commercial and technical aspects of producing asset information.
- Project Information Requirements (PIR) that explain the information needed to answer or inform high-level strategic objectives within the appointing party in relation to a particular built asset project.
- Exchange Information Requirements (EIR) set out managerial, commercial and technical aspects of producing project information. In general terms, EIR consolidates the OIR, AIR, and PIR into a structured contractual framework to define clear expectations for project information deliverables, data formats, and information handover processes.

Information models are made up of one or more information containers. An information model is a collection of information containers, however they are created or presented. Information models exist at asset, project and delivery team levels [22]. The Asset information model (AIM) supports the strategic and day-to-day asset management processes established by the appointing party. It can also provide information at the start of the project delivery process. The Project information model (PIM) supports the delivery of the project and contributes to the AIM to support asset management activities. The PIM should also be stored to provide a long-term archive of the project and for auditing purposes.

Information exchanges, at all levels, involve the sharing and coordination of information through a Common Data Environment (CDE), using clearly defined operating procedures to enable a consistent approach by all organizations involved and streamline flow of validated and accessible information. The CDE is a central tenet of the BIM framework, providing an integrated digital space where all project information is stored, managed, and disseminated. It typically include a standardized structure for data storage, a clear set of procedures for data management, and a suite of tools for data access and revision control. It is structured to support the information delivery cycle of a project from the conceptual stage through design, construction, and operational phases, facilitating the BIM process's collaborative essence. It must be mentioned that the, within the BIM, a CDE represents both technology (the 'CDE solution') and a process (the 'CDE workflow'). To fully realize the BIM promise of interoperability, the buildingSmart organization [23] have developed the openBIM® to enable seamless data sharing and collaboration across platforms and stakeholders, while maintaining full flexibility in defining specific workflows. At i's core, openBIM is enabled by a series of protocols as presented in Figure 4, for a generic workflow.

Where Use Case Management (UCM) is a service that captures, specify and, exchanges industry best practices; Industry Foundation Classes (IFC) [24] is a set of standardized, digital descriptions of the built asset industry; Information Delivery Specification (IDS) is a standard for defining and checking information requirements in a computer interpretable form to ensure data quality; buildingSMART Data Dictionary (bSDD) is a service for publishing and accessing terms and definitions that describe the built environment to increase data consistency; BIM Collaboration Format (BCF) is a standard communication protocol for efficient issue management and coordination.

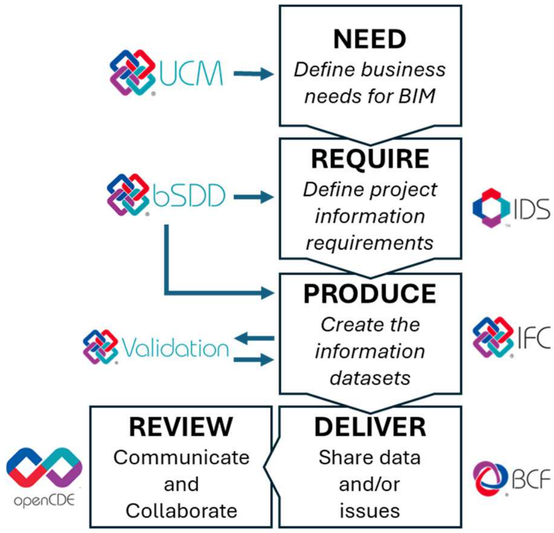

Fig. 4. openBIM information flow.

5. CONCLUSION

This paper presented a novel framework for enhancing decision-making, quality control, and asset management of welded steel bridges through the integration of BIM, digital manufacturing, and predictive maintenance.

A key contribution of this research is the introduction of the "backward standard correlation" approach, which ensures that operational requirements, such as inspection strategies, maintenance needs, and manufacturing constraints, are considered from the earliest stages of the design process.

The findings demonstrate that BIM-enabled workflows supported by specific standards [21], [24], coupled with a robust understanding of the technical requirements (presented in detail in [25]), the structural Eurocodes [1], [6] and SR EN 1090-2 [2] standard, can significantly improve the efficiency and reliability of bridge construction and maintenance.

By leveraging digital technologies and embracing a collaborative approach among stakeholders, asset owners can optimize project delivery, reduce lifecycle costs, and ensure the long-term safety and sustainability of their bridge infrastructure.

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Asigurarea integrității structurale a podurilor metalice sudate prin managementul inteligent al informațiilor de-a lungul ciclului de viață

Această lucrare propune un cadru bazat pe BIM pentru îmbunătățirea deciziilor, a controlului calității și gestionării activelor. Prin integrarea testării nedistructive și mentenanței predictive, metodologia abordează provocări precum oboseala materialelor, degradarea și conformitatea cu cerințele SR EN 1090-2. Conceptul de „corelare inversă a standardelor" asigură integrarea cerințelor operaționale în proiectare, optimizând costurile și reducând riscurile. BIM facilitează monitorizarea în timp real, colaborarea eficientă și schimbul structurat de informații în cadrul unui mediu comun de date. Lucrarea susține tranziția spre Industry 5.0 și oferă o metodologie scalabilă pentru digitalizarea proceselor asociate proiectării, execuției și monitorizării podurilor metalice sudate.

Cuvinte cheie: *Modelarea informațiilor despre construcție (BIM), Producție digitală, Poduri din oțel sudate, Clasa de execuție, Testare nedistructivă (NDT), Evaluarea daunelor cauzate de oboseală*

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