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Digital twins in bridge engineering for streamlined maintenance and enhanced sustainability

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A B S T R A C T

Digital twins are evolving to oversee the entire construction life cycle, with a strong emphasis on sustainability across environmental, financial, regulatory, and administrative dimensions. This paper introduces a methodology for managing existing bridges through an adaptable digital twin. The aim of this research is to develop a framework for constructing digital twins that, by enabling structural analysis and "what-if" scenario simulations, supports more reliable maintenance decision-making. Such type of digital twin ensure safety, extend lifespan, and provide a precise database for managing end-of-life processes within a circular "cradle to cradle" framework. This methodology also addresses obsolescence issues related to software evolution and the longer lifespan of a bridge compared to its creator. A case study demonstrates the methodology's effectiveness, showing that digital twins can be flexible, cost-effective tools for managing all types of bridges, including small and existing ones.

1. Introduction

Failures in bridges and infrastructure result in significant economic losses and, in many cases, loss of life [1–3]. Additionally, these failures often have a profound emotional impact on communities, similar to other types of traumatic events [4,5]. *As illustrated in Fig. 1, except for unpredictable extreme events, all causes of bridge collapse have known causes.*

Bridges in service are subject to degradation processes influenced by material properties, mechanical loads, and environmental factors. [7–9]. Despite safety factors designed to reduce uncertainties and extensive research aimed at avoiding design errors and ensuring maintenance, bridges naturally undergo performance degradation over time. In principle, for a well-designed structure, the loss of performance is slow and manageable, but without an appropriate inspection and maintenance plan, the risk of an acceleration in the deterioration of performance leading to service and safety problems is amplified [3,10–12]. *Moreover, existing structures were designed under different conditions and standards that have evolved over time* [13–15].

For decades, tools like Finite Element (FE) software have been used to build digital models of bridges to analyze how performance changes due to degradation or increased loads. These models have improved the safety, serviceability, and lifespan of bridges, but they have limitations. They are software-specific (i.e., they become useless if the software is unavailable) and lack interoperability, meaning a model created for structural analysis cannot be used with other software.

Building Information Modeling (BIM) has partly addressed these limitations and promoted the development of new models known as digital twins (DTs). Borrowed from other industries, DTs are digital representations of physical counterparts, integrating all the characteristics of the physical entity into a single platform.

This research aimed to develop a methodology for establishing a DT for existing bridges that can evolve alongside its physical counterpart. The DT can then be used to manage maintenance operations following a "cradle to cradle" logic. In this context, adopting a "cradle to cradle" approach means that, at the end of the bridge's life, the DT will serve as a precise database of its composition, facilitating the efficient reuse or recycling of the bridge.

1.1. Literature review

DTs offer potential for effective maintenance management and are increasingly recognized among emerging systems. Generally, a DT refers to a digital version of a system, component, or asset [16]. Although the definition of DT remains debated, it is commonly described as a "digital representation of the physical asset that can communicate, coordinate, and cooperate in the manufacturing process to improve productivity and efficiency through knowledge sharing" [17]. This broad definition

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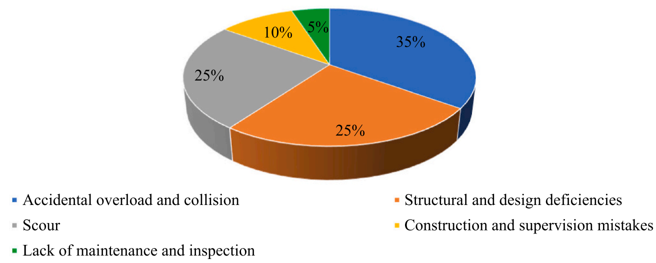

Fig. 1. Distribution of causes of bridge collapse [6].

encompasses DTs across various industries but is not specific to civil engineering. In general, the models developed for bridges often lack real-time updates and communication with their physical counterparts, preventing two-way interaction and effectively making them digital shadows rather than true digital twins. Nevertheless, the term "digital twins" for these "digital shadows" has become so common in bridge engineering that it will be used in the following sections. It is important to note that the extension of the term "digital twins" to "digital shadows," as observed in the literature, could lead to confusion or misaligned expectations in the future.

According to [16], a DT can be categorized by its level of sophistication/maturity: pre-digital twin, digital twin, adaptive digital twin, and intelligent digital twin. These categories differ based on the existence of a physical twin, data acquisition methods, and the use of machine learning for system/environment interaction. Bridge engineering DTs are classified as 'digital twin – level 2,' which means they include performance, health, and maintenance data from the physical twin and receive batch rather than real-time updates. The essential features of a bridge DT, as summarized in [18], include: a digital replica of the physical structure, data as a core component, near-real-time updates, life-cycle data integration, a common data environment, and its function as a simulation and visualization tool for risk assessment, collaboration, and predictive performance. Additionally, it leverages real measurement data to enhance future projects and practices. *These characteristics make DTs particularly suitable for managing bridge structures, which require continuous monitoring and adaptive maintenance strategies.* [19].

Regardless of DT classification, DT models are sometimes seen as an unnecessary cost, particularly when the owner lacks the expertise and personnel to use them effectively, and the bridge in question does not face significant challenges or holds reduced relative importance. Nevertheless, whether small or large, a bridge remains a crucial part of the economy and society, with a lifespan likely to outlast the citizens who use it. Small bridges punctuate the landscape of a country, and their management by small towns can become challenging, leading to substantial costs for repairs or strengthening operations necessary to ensure safety and serviceability. *Sometimes, societal changes may require an old local bridge to support much heavier loads than anticipated at the time of its construction, as it now falls within a heavy-load transportation route leading to a motorway.* In such cases, a DT can provide a better means to ensure necessary public service and keep costs under control. Indeed, a DT enables service life prediction, anomaly detection, seismic collapse assessment, and structural health analysis [20,21]. These functionalities are achieved through the integration of FE methods and data-driven approaches [22].

Recent efforts on DTs focus primarily on geometric reconstruction and [23] and physical-digital interaction [24]. In terms of geometric reconstruction, advancements in laser scanning techniques have enabled scan-to-BIM processes that accurately reproduce the geometry of existing structures in digital form. However, real-world complexity often exceeds model representations, making models based solely on laser scanning generally unsuitable for bridge safety and serviceability analyses or vulnerability assessments, even with AI-assisted defect detection through image analysis. Therefore, once the model obtained from laser scanning is converted into an open format and interoperable DT, it is essential to incorporate the specific characteristics of the structure and inspection results [25,26] to achieve an accurate representation of the real structure and meaningful prediction of its performances. Other advancements concern the interaction between the DT and its physical counterpart for structural health monitoring, achieved through the integration of sensors that measure critical metrics [27–29].

However, as stated in [20], challenges remain, particularly in simulation and the development of "what-if" scenarios for assessing asset risks and predicting performance. Addressing these challenges necessitates a comprehensive methodology and appropriate ontology to ensure interoperability and effective knowledge sharing among stakeholders [30].

A well-constructed DT can have a synergistic effect that enhances long-term sustainability. Open formats and interoperability enable more effective knowledge sharing among professionals working on the same project. They also allow owners greater flexibility in choosing consultants for various maintenance operations or collaborating with other owners to optimize life-cycle management costs. Open formats and interoperability help address software obsolescence issues and ensure continued use of the DT even if the original developer is no longer available. Additionally, these features aid owners, especially institutional ones, in sharing knowledge and collaborating to reduce operational costs while increasing safety, serviceability, and the lifespan of structures.

Knowledge sharing can be maximized through interoperable formats like IFC [31,32], which aim to ensure interoperability among AEC/FM industry software applications. Leveraging semantic modeling at the intersection of IoT and AI, IFC robustly supports the development of DTs [33–35]. In bridge engineering, IFC has been used for two main purposes: detecting degradation and real-time monitoring. For example, IFC has been used for spalling detection from point cloud data [25], damage visualization through image processing [26] and real-time monitoring using artificial neural networks based on structural analysis [36]. Despite various efforts to enhance comprehensive knowledge sharing, a methodology that addresses the challenge of software obsolescence, while also enabling the creation of "what-if" scenarios, has yet to be found.

Structures like bridges require ongoing structural analyses to assess safety and serviceability after exposure to loads and environmental effects. Therefore, an interoperable DT must be open with an ontology able to accommodate the effect of degradation phenomena and the results of monitoring activities [31,37,38]. The DT model should also be easily transferable to a FE method software specialized for structural analysis and offer sufficient flexibility to integrate inspection and monitoring data seamlessly.

1.2. Problem statement

Bridges are owned by a diverse range of entities, from large organizations like the Swiss Federal Roads Office (FEDRO), which manages hundreds of bridges, to small rural villages overseeing only a few. These owners face a common challenge: the need for DTs that are tailored to the specific characteristics of each bridge and capable of evolving alongside their physical counterparts by integrating data from regular inspections and monitoring [20,39]. While these capabilities are essential for ensuring safety, serviceability, and effective maintenance planning, existing DTs often fall short in meeting another critical need—interoperability across various software platforms.

Public entities typically outsource DT development to engineering firms or universities, resulting in multiple models created with different software that often become obsolete within a few years. This fragmentation can lead to inefficiencies, particularly when new professionals are unable to use these models, necessitating the development of new ones. To address these challenges, DTs must be interoperable and use open formats, ensuring they remain functional across different software used by architects, land surveyors, structural engineers, and others.

Moreover, the longevity of bridges and the evolving nature of their environments demand flexible DTs that can adapt to new scenarios and expand as needs arise without altering their core principles. Rather than merely listing advanced features, the focus should be on developing a robust methodology for constructing DTs that can be easily updated and remain relevant over time.

1.3. Research contribution

The overarching goal of this research is to establish a methodology for constructing Digital Twins (DTs) that support structural analysis and maintenance decision-making, with a particular focus on enabling “what-if” scenario simulations. This approach ensures that maintenance strategies can be explored and optimized without altering the core working principles of the DT, while also being flexible enough to accommodate other applications.

To be effective, these models must accurately represent reality and integrate all relevant data collected during inspections. Such dynamic models enable professionals to operate the DT using their specialized software.

The methodology is demonstrated through a real case study of the Praz bridge, which illustrates how laser scanner technology, combined with an appropriate BIM ontology, contributes to creating an open and interoperable DT. This DT evolves over time by integrating observed degradation effects, serving as a tool for structural analysis and maintenance. It also permits the evaluation of structural safety and serviceability under multiple hazard scenarios based on the potential evolution of these degradations and facilitates the efficient management of the bridge’s end-of-life in a circular logic.

Additionally, a low-cost monitoring methodology applied to the Grandson bridge highlights how software obsolescence and the retirement of engineers had previously hindered the use of valuable technology. This example underscores the need for open formats and interoperable DTs and demonstrates how a well-constructed DT can prevent the loss of critical information.

1.4. Paper organization

The paper is organized as follows:

(i) The ‘Materials and Methods’ section provides a detailed description of the methodology used to create a DT capable of conducting scenario-based analyses while ensuring interoperability.
(ii) The ‘Results’ section presents and analyzes the application of the proposed methodology to a real case study involving the Praz Bridge. This case study evaluates structural simulations under various hazard scenarios, highlighting the integration of detected degradation for improved maintenance decisions.
(iii) The ‘Discussion’ section examines how the challenge of obsolescence becomes a critical issue for structures without a DT. The Grandson Bridge case study highlights the crucial role of DTs in ensuring long-term viability. It demonstrates that, although low-cost monitoring systems offer potential, they are ineffective without a DT to support continuous updates over time.
(iv) The ‘Conclusions and future work’ section summarizes the findings and outlines directions for future research.

2. Materials and methods

2.1. Objectives and the methodology definition

To achieve the objectives and address the gaps highlighted in the problem statement (see Section 1.2), the project aimed to create a digital representation of an existing bridge, capturing the shape of each element, their characteristics, and their assembly. A key objective was to consolidate all available data related to the bridge’s structural health into a comprehensive digital model. Another primary goal was to develop a digital representation compatible with various specialized software, including structural engineering, land surveying, and architectural tools. The digital model needed to integrate relevant data from specialized analyses seamlessly and be readily updated with future monitoring and inspection results.

This need for up-to-date data was inspired by the author’s previous research on structural health monitoring, alarm systems for safety risks, and maintenance of existing structures. Despite the success of these studies, many results were lost due to the obsolescence of commercial and proprietary software and the non-interoperable nature of models developed with these tools. The impact of analyses on structural behavior was also limited by outdated FE models, which could not be easily updated with new data. The envisioned digital representation is, in fact, a DT created through a general methodology, the workflow of which is illustrated in Fig. 2.

In the specific case study of the Praz Bridge, the general workflow outlined in Fig. 2 is tailored to the available databases and the specific requirements of the scenarios needed for assessing the bridge’s safety (see Fig. 3). Consequently, the procedure is divided into three steps, which are detailed in the subsequent sections.

2.1.1. Step 1: Data collection and BIM model creation

The first step in the methodology focused on identifying the best method for collecting data on an existing bridge. Laser scanners, known for their high performance, are effective in capturing the shape of a bridge and its surroundings. However, this digital model must be refined to isolate each individual element and define their assembly. The transition from a laser scan model to a BIM model can only occur if relevant data on the structural materials and elements are available. The definition of the semantic model and ontology, which completes step 1, must also consider all foreseeable uses of the DT. For example, while analyzing the interaction between the soil and the structure might seem unlikely for a bridge, the BIM model must be prepared to incorporate geotechnical parameters of the foundation soil into the DT at any time. Additionally, the BIM model should be operable within specialized software for soil-structure interaction analysis. Further explanations on the first step are provided in Sections 3.2 and 3.3, where the “Scan to BIM” step of the methodology is implemented on the “Praz” concrete bridge, owned by FEDRO, with detailed characteristics presented in Section 3.1.

2.1.2. Step 2: From a BIM model to a DT

The second step of the methodology involves transforming the BIM model into a DT by enriching it with all available information on the bridge. As mentioned in the first step, the BIM model is prepared to accommodate all relevant data. Step 2 highlights the fundamental importance of the information available on an existing bridge. Swiss Norm 469 stipulates that construction owners must maintain records of all relevant property information, including original plans, maintenance operations, and consultant reports [40]. However, not all owners have complete documentation, particularly for older constructions. In contrast, large organizations like FEDRO have created comprehensive databases containing all available information on their structures, which are constantly enriched with new data collected, reported, and inputted using strict procedures to ensure quality and usefulness [41]. The existence and quality of this database are crucial for creating a DT that evolves over time alongside its physical counterpart. A lack of data or inconsistently structured data will hinder the conversion of a BIM model into an evolving DT. Section 3.4 demonstrates how the BIM model of the Praz Bridge was enriched with data extracted from FEDRO ‘s Kuba database [41].

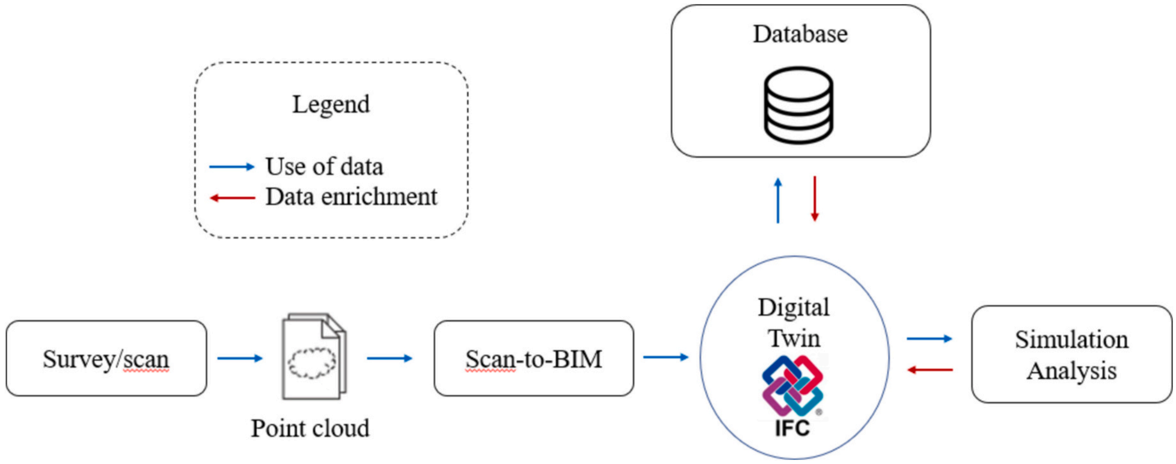

Fig. 2. Optimized workflow of the methodology proposed to construct a DT.

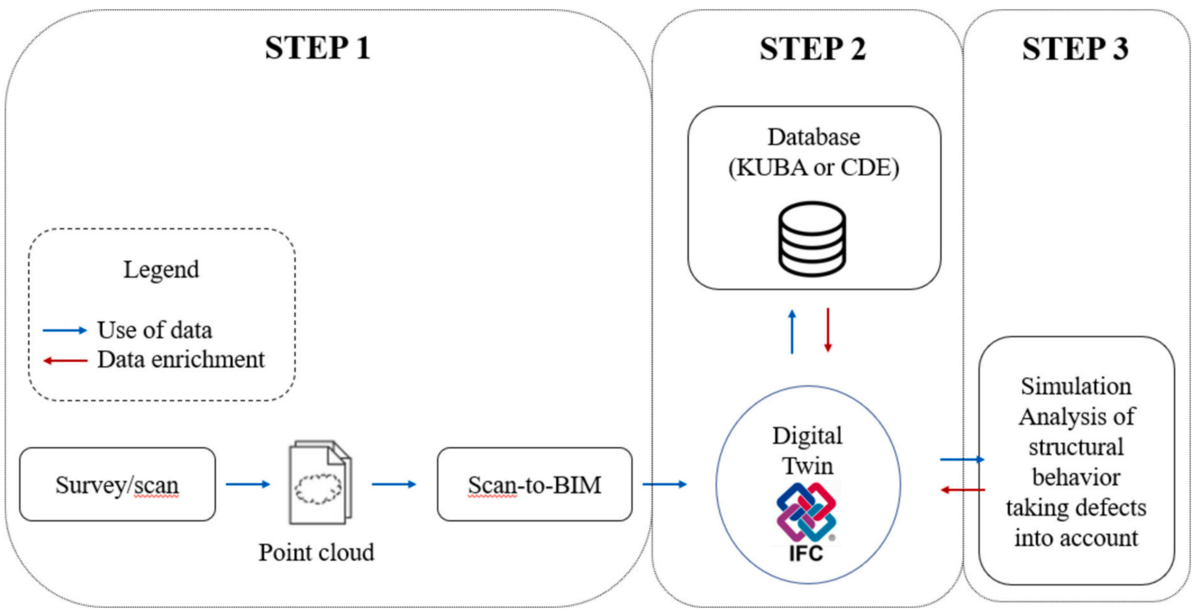

Fig. 3. Optimized workflow of the methodology proposed to construct the DT of the Praz Bridge.

2.1.3. Step 3: Acquisition of the DT into specialized software

Once the DT is constructed, it becomes possible to import the DT of a bridge into specialized software for advanced analyses. This use of the DT is an outcome of the methodology rather than a step within it. In fact, the analyses conducted with specialized software contribute to the database, making the DT continuously evolutive. The interoperable and open-format nature of the DT obtained in step 2 allows for the quick acquisition of the DT in most specialized software used in bridge analysis. The model acquired often needs further adaptation for certain analyses, though this process is much quicker than building a model from scratch. Section 3.5 illustrates this process for the Praz Bridge, where the DT is imported into a structural FE software, adapted to the specific analysis, and further modified to account for the loss of performance in certain structural elements due to ongoing corrosion. If the structural analysis indicates that the bridge's safety is at risk due to corrosion, this will trigger urgent action by the owner to mitigate risks and quickly prepare a plan to restore the required safety level.

2.2. Hazard scenario analyses using the DT

The characteristics of DTs prepared using this methodology also allow for the analysis of multiple hazard scenarios in the evolution of structural health, enabling informed decisions about the timing of specific maintenance operations. This capability is demonstrated in Section 3.6 for the Praz Bridge. A column exhibiting a certain degree of corrosion at the present time does not pose safety concerns. However, a scenario projecting the progression of corrosion over time is simulated, and the column's safety is reassessed. The results show that under this scenario, safety will not be compromised, indicating that while maintenance should be planned, it is not yet urgent.

2.3. Addressing the obsolescence issue

As previously mentioned, the need for this methodology arose from the authors' past experiences. The case of the Grandson Bridge, owned by FEDRO, illustrates how a DT prepared using the presented methodology could have prevented the loss of valuable data and models due to the lack of interoperability in the original digital model. Section 4 discusses the Grandson Bridge case, highlighting the process of constructing the FE model of the bridge using KUBA data and the implementation of a low-cost yet efficient monitoring system. It also demonstrates how a DT similar to the one developed for the Praz Bridge could have prevented the obsolescence of the digital model, allowing the owner to retain and repurpose it for other uses. Finally, Section 4.5.3 presents further lessons learned from the Grandson and Praz cases, particularly on how a DT could be adapted to monitor a bridge effectively.

3. Results

3.1. General characteristics of the Praz bridge

The studied bridge is located in Bellaigues (Switzerland), in the section 31 Vallorbe - Essert-Pittet. The Praz bridge is a continuous box girder bridge with a width of 14.96 m and a total length of 377.60 m, comprising a total of 9 spans. In Fig. 4, the original drawings illustrate a comprehensive depiction, including a plan and elevation view of the entire bridge, a cross-sectional view of the deck, and details of the direct foundations between piles 2 and 5. Materials used have been determined based on the planning and the calculation report. Specifically, concrete with a $f_{cd,28}$ of 44 MPa and steel with a f_{yk} of 400 MPa have been employed.

3.2. Data acquisition methods for 3D model development

Due to the bridge's dimensions, laser scanning technology has been selected for the precise assessment of its geometry. This process generates a 3D point cloud, with multiple scans required to capture the entire structure comprehensively. The primary tool used for measurements is a RIEGL VZ-2000i laser scanner. Additionally, a Leica GS18 GNSS receiver and a TS16 total station were used to establish a reference point network. The placement of reference points is crucial, as poor distribution can result in low-quality alignment. Furthermore, the quality of measurements depends on various parameters reported in Table 1.

Table 1
Measurement parameters for 3D laser scanning.

Parameters	Settings
Number of measurements	~500,000/s
Maximum distance	600 m
Precision	3 mm at 100 m
Accuracy	5 mm at 100 m
Laser diameter	~3 cm at 100 m

Fig. 5 illustrates the distribution of scan locations and reference points during the measurement process of the Praz bridge. The placement of these locations is influenced by both, topography and natural obstacles. Notably, a deliberate decision was made to position numerous reference points beneath the bridge at regular intervals. In this instance, existing points on each pile of the bridge were utilized, supplemented by the addition of new points around them to enhance network density and improve alignment.

For this project, the RiSCAN software [42] is used, employing an additional technique that involves automatic plane detection within point clouds. This is followed by identifying optimal correspondences between these planes, aligning with the point-cloud-to-point-cloud alignment concept. With the known MN95 global coordinates of the control points, georeferencing the assembled point cloud is straightforward. Fig. 6 displays the assembled point cloud, where the color of each point indicates its originating scan. It is important to observe that the quantity of measured points may exceed the requirements for subsequent steps in the process. To avoid unnecessary data usage and reduce file size, point subsampling is essential. Cyclone 3DR software [43] was employed for this purpose, utilizing a method that aimed to retain at most one point every 5 cm.

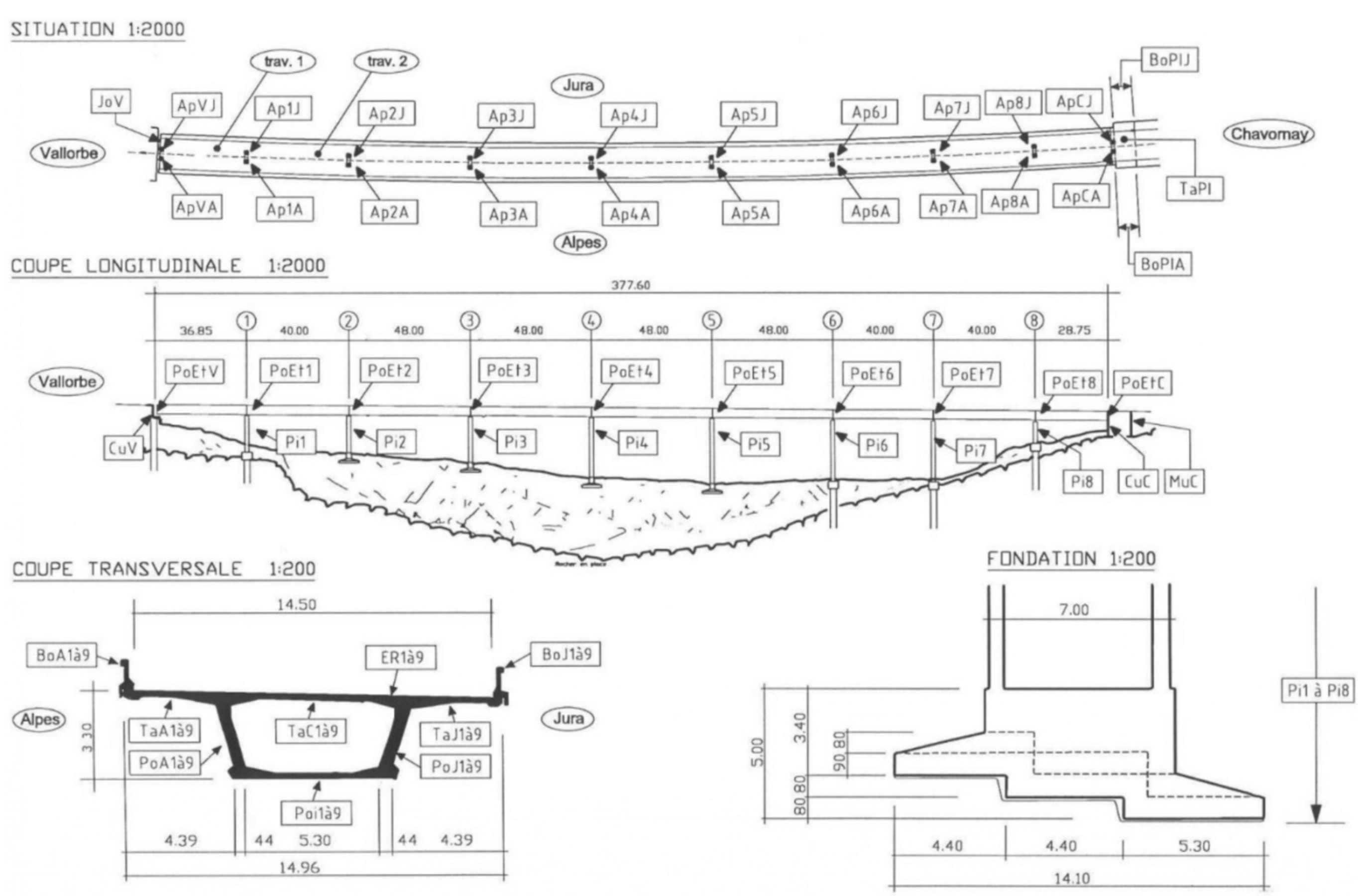

Fig. 4. Comprehensive illustration of bridge Praz: plan, elevation, cross-section, and foundation details.

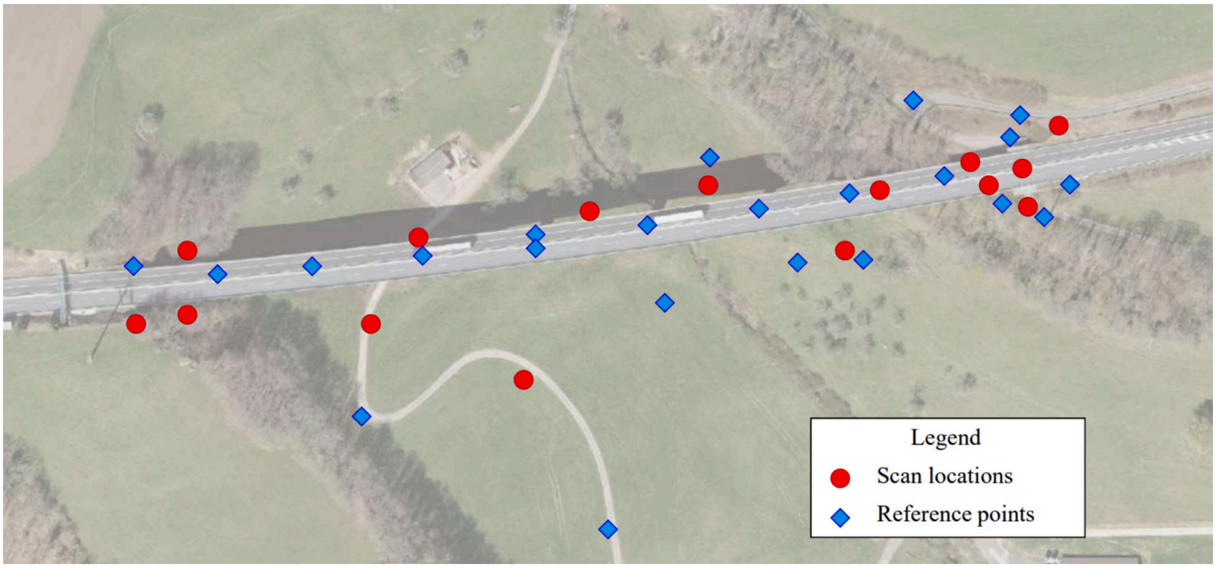

Fig. 5. Locations of scans and reference points on the Praz bridge.

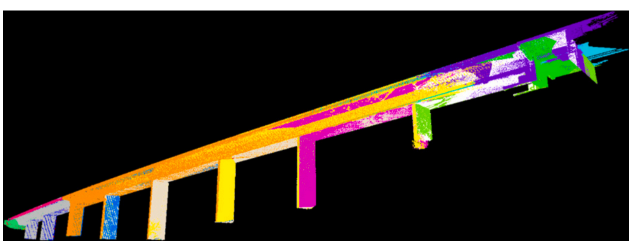

Fig. 6. Point cloud of the Praz bridge.

3.3. Scan-to-BIM process

As the geometry is obtained, a semi-automated procedure is applied to create a numerical BIM model in the interoperable IFC 4.3 format.

The three main steps of this scan-to-BIM process are schematically represented in Fig. 7. These steps include semantic segmentation, 3D shape reconstruction, and BIM model preparation [38].

The first step involves semantic segmentation, aiming to segment the built asset by automatically detecting its components. The methodology used for this purpose is based on the template-matching algorithm.

The template matching technique in computer vision precisely locates elements in an image, referred to as the "source image." This technique requires both the source image and a template image containing the pattern. In our study, source images are cross-sectional views of the bridge, obtained from subsets called "slices" of the point cloud. Each slice corresponds to a different source image. Template images display transversal views of components, defined manually. Once a component is identified in a source image, points are extracted from the slice and labeled. This iterative process continues until all slices are analyzed. The stages of the semantic segmentation process are illustrated in Fig. 8, with further details provided in [31].

The second step involves 3D shape reconstruction, for which Rhino software was utilized as a platform for the DT [44]. After the semantic segmentation, where bridge components are identified and separated, the data is imported and structured. Initial geometry creation in Rhino + plugins "Remesher" produces a preliminary mesh. This mesh is refined in SketchUp Pro [45], yielding an enhanced mesh that is re-imported into Rhino to finalize the geometry creation.

The BIM model closely approximates measurements obtained through laser scanning, with an average deviation of less than 7 cm. Fig. 9 illustrates the degree of deviation between the BIM model and the point cloud, expressed in centimeters.

3.4. Enrichment of the BIM model (BIM to DT)

The model was manually enriched with information from the FEDRO -provided KUBA database, which serves as the primary repository for all plans, interventions, and documents related to structures owned by FEDRO [41]. This database also contains regular and extraordinary inspection reports. Its purpose is to display the degradation status of various elements, aiding engineers in assessment. The visualization model, as illustrated in Fig. 10, indicates the location and severity of

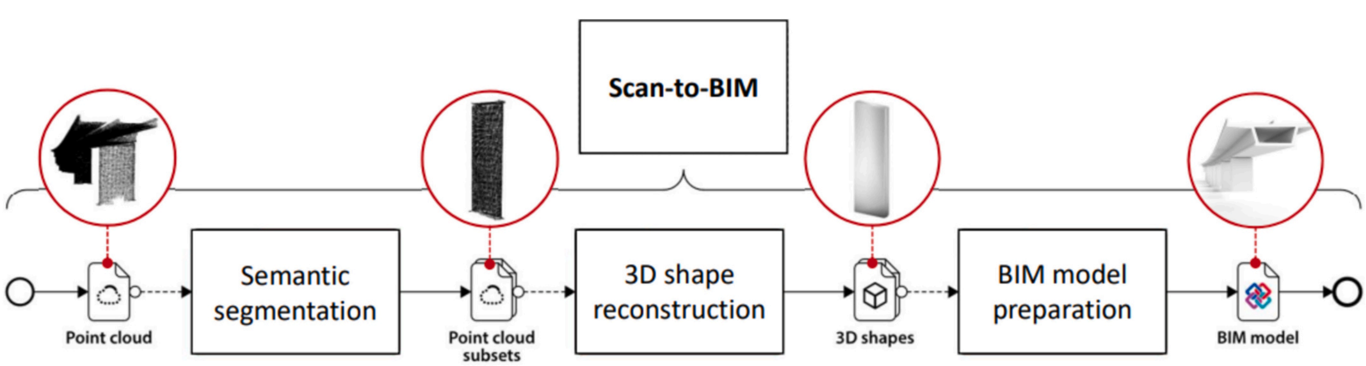

Fig. 7. Scan-to-BIM process overview for creating an IFC 4.3 compatible numerical model (Image courtesy of B. Domer, HEPIA).

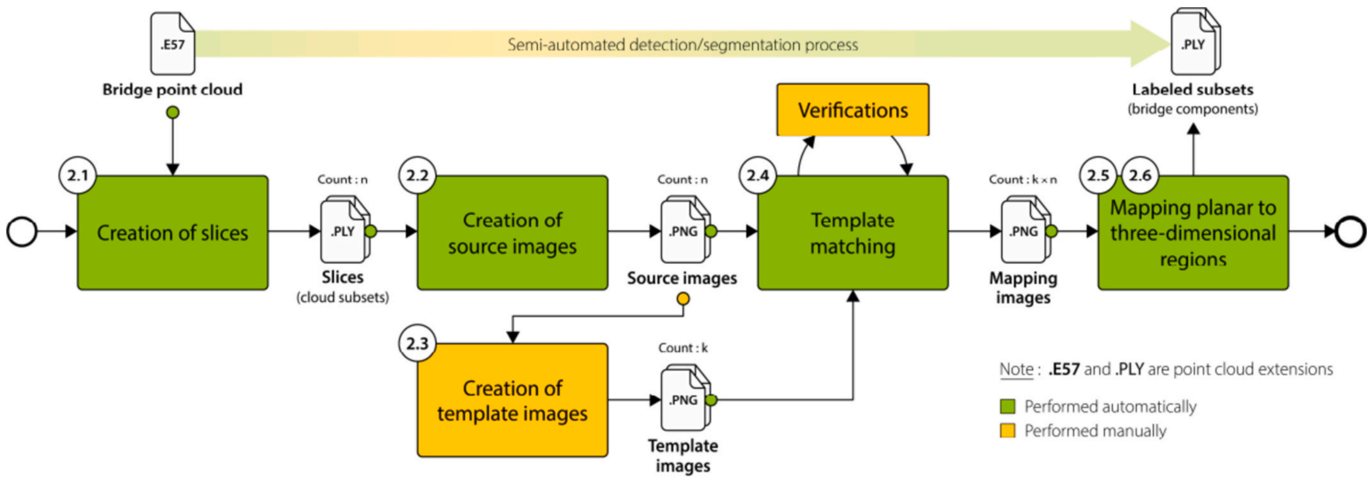

Fig. 8. Workflow of semantic segmentation stages [31] (Image courtesy of B. Domer, HEPIA).

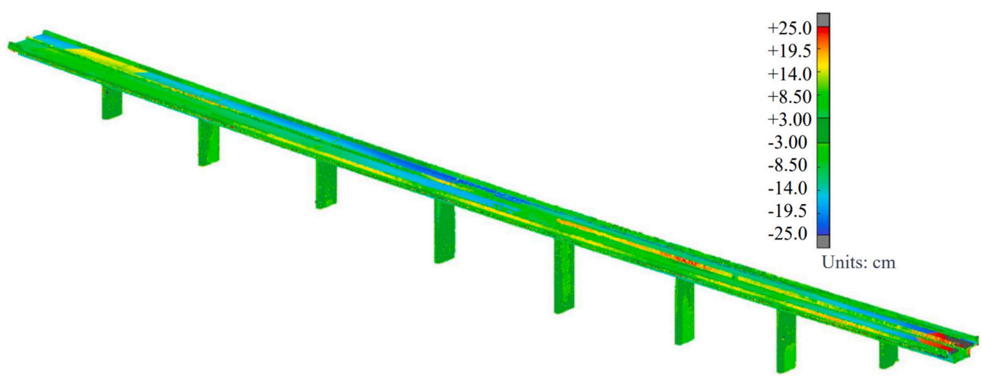

Fig. 9. Deviation between the BIM model and the point cloud (Image courtesy of B. Domer, HEPIA).

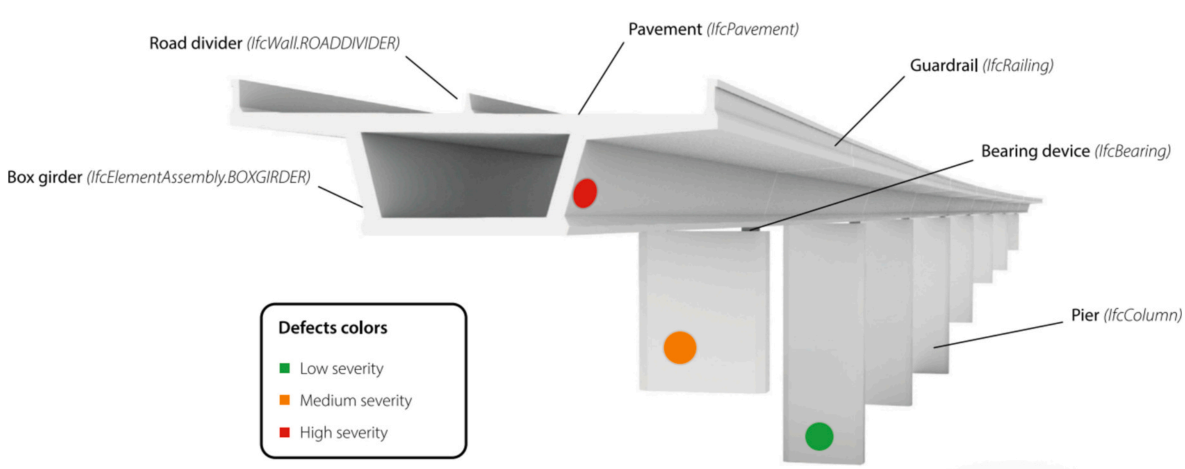

Fig. 10. Degradation visualization model of the Praz bridge [38] (Image courtesy of B. Domer, HEPIA).

degradation using a scale from 1 (good) to 5 (urgent intervention required), in accordance with FEDRO's guidelines [46]. It also offers detailed insights into the causes or agents of specific degradations. In fact, this model integrates all relevant information from plans and inspection reports for each structural element, presented in a user-friendly manner as depicted in Fig. 11. The proposed approach does not enable automatic defect detection. Instead, it serves as an integrated visualization tool within the database. It comprehensively encompasses all relevant information for analyzing the structural element, including degradation models. This model possesses the capability to integrate a wide array of file formats, encompassing not only verbal inspection reports but also derived data such as degradation models and information pertaining to load-bearing capacity.

Once the point cloud collected using the laser scanner is transformed into a DT model, structural engineers will have the capability to analyze the structure. By integrating the degradation data, they can assess if and to what extent the load-bearing capacity of the structure is diminished due to these deteriorations, and they can also analyze different evolution

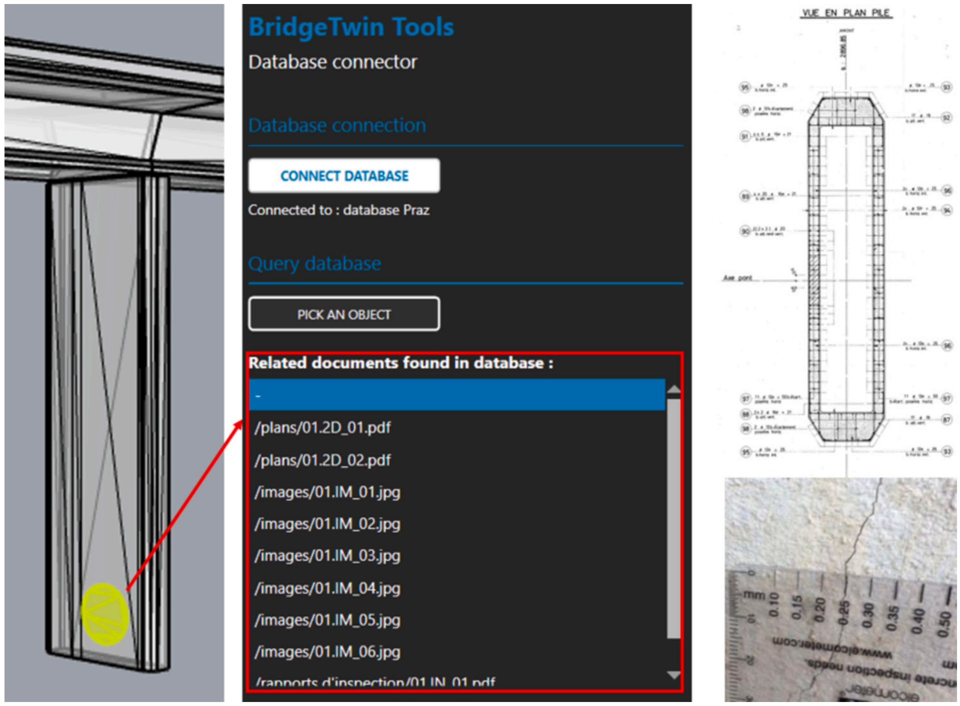

Fig. 11. Degradation visualization model for pile 5 of the Praz bridge (Image courtesy of B. Domer, HEPIA).

scenarios.

3.5. *Importation of the DT on a structural finite element model (Praz bridge)*

The FE model is generated by importing the previously generated IFC file format into SCIA Engineer software [47]. This is a semi-automatic procedure because the resulting model contains information about geometry and materials but not about finite elements, boundary conditions, and loads. The creation of the FE model involved a process of converting "generic volumes" into 1D beam elements, arranging constraints, and applying loads. At the foundation level of the piles, fixed supports were applied as base constraints, while the connection between piles and beams was achieved by introducing support devices (fixed, unidirectional, and multidirectional) according to the bridge's design. In Fig. 12 is reported the solid and the single-line FE model views. The average size of a 1D mesh element is set to 200 mm.

For load application, the chosen combination maximized the moment at the base of the pile 5. The considered loads and their combination coefficients are listed in Table 2 according to [48]. The load combination corresponding to the Ultimate Limit State (ULS) was then analyzed statically, determining normal force and bending moment at the base of the pile 5 as 23,717 kN and 35,289 kNm, respectively.

Table 2
Load and combination coefficient.

Loads	Values	Safety coefficient	Combination coefficient
Self-weight (structure)	25 kN/m^3	1	–
Paving	21.78 kN/m	1	–
Central Guard-rail	3.75 kN/m	1	–
External guard-rail	6.45 kN/m	1	–
Wind	0.9 kN/m^2	1.5	–
Traffic –lane 1 distributed	27 kN/m	1.5	0.4
Traffic –lane 1 tandem	300 kN	1.5	0.75
Traffic –lane 2 distributed	7.5 kN/m	1.5	0.4
Traffic –lane 2 tandem	200 kN	1.5	0.75

3.6. *Praz bridge: Structural verifications for different hazard scenarios*

Based on inspections of pile 5 on the Praz bridge, no corrosive phenomena were found. Consequently, a flexural verification of the actual state of pile 5 was performed. Due to a lack of material data and the absence of a testing campaign, safety coefficients for knowledge level 1 (KL1) were applied according to the NTC2018 standard [48] (a factor of 1.35 for KL1). Fig. 13 illustrates the flexural verification of pile 5 under

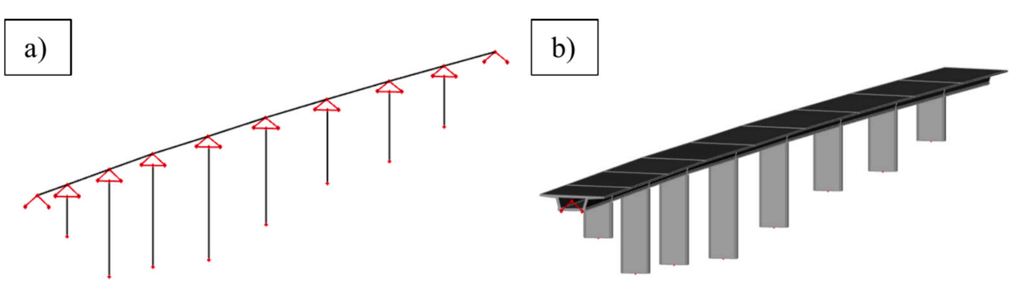

Fig. 12. FE model (Praz Bridge): a) single-line view, b) solid view.

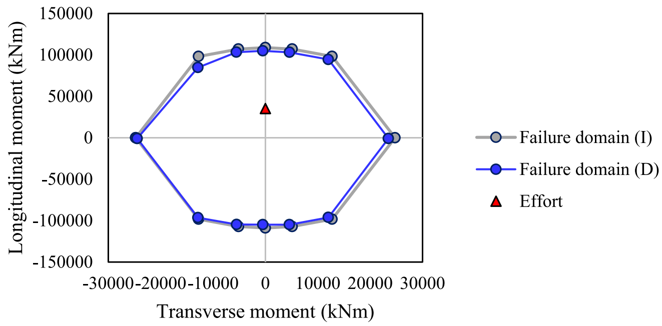

Fig. 13. Bending investigation for pile 5 at the normal stress value of 23,717 kN.

real conditions, indicating the failure domain as “failure domain (I).” It is arguable that the current structure is in good health, at least for the time being. However, with the realized DT, future inspections and monitoring can assess structural health.

To demonstrate the capabilities of the DT, an additional analysis was conducted under degraded conditions. Assuming a 40 % reduction in the resistant section of the rebars, local corrosion in the longitudinal bars due to chlorides was postulated, as shown in Fig. 14. Fig. 13 depicts the flexural verification of pile 5 under degraded conditions, highlighting the failure domain as “failure domain (D)”.

Structural verification was performed by importing geometry and material properties into VCA-SLU software [49], where resistance domains were compared with FE model derived stresses. Visualizing degradation on the DT, which includes inspection data and corroded bar placement, enables faster implementation than traditional methods. Additionally, it facilitates future enrichment of the DT model with structural details, such as resistance domains of various structural element.

Despite the significant amount of assumed reinforcement loss due to corrosion, the verification remains satisfactory for the bending moments in both the longitudinal and transversal directions. However, this scenario could be critical for the stability of the pile, as corrosion of the longitudinal rebars could compromise the horizontal rebars (functioning as ties), thus increasing the buckling length of the corroded longitudinal rebars under both static and dynamic loads.

Bridge inspections typically furnish the essential details to define the resilient steel reinforcement section. However, they sometimes lack some of the parameters required for constructing the corrosion model [50]. Even if such parameters are unavailable from on-site analyses, the periodically enriched DT, with the results of regular inspections, becomes an efficient database for developing a genuine corrosion model. This involves deriving degradation laws through interpolations of properties over time, as well as requesting the collection of relevant data during subsequent regular inspections.

Moreover, the open format and interoperability of the DT empower bridge owners to conduct analyses using their preferred software or engage any consultant, all without incurring additional expenses for model reconstruction or reanalysis.

To further emphasize the importance of scenario modeling using DTs, the case of the Gerber saddles is considered [51]. Gerber saddles have been popular for a long time as they allow for a point where bending moments are forced to be zero. However, a significant issue with this element arises from the joint placed there, which over time may develop water leakage containing heavy doses of deicing salts. The wet/dry conditions will promote a fast corrosion of the reinforcement of the Gerber saddle and the degradation of the concrete. Since Gerber saddles are inherently difficult to inspect, any signs of problems in this element or leakage of the joints should prompt careful scenario analyses and in-depth inspections, as the failure of the saddle could lead to the failure of the bridge, as seen in the unfortunate case of the Concorde bridge [52].

The Gerber saddle and the Concorde bridge serve as examples of a vast array of elements and cases where a digital twin could help save lives and ensure the safety and service life of capital cost structures in a more efficient manner.

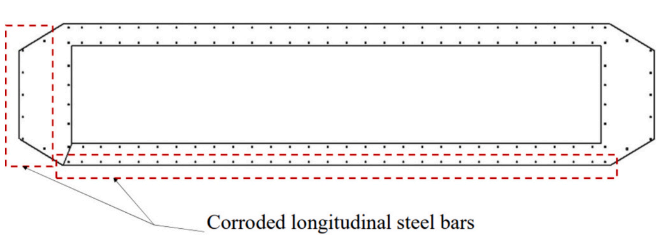

Fig. 14. Disposition of the corroded longitudinal steel bars.

4. Discussion

4.1. Technological obsolescence in bridge management

In the past, the challenge of monitoring small bridges that did not exhibit critical behavior but had surpassed their design life was addressed through a low-cost methodology. This approach, developed by land surveyors, was based on diachronic image correlation and could be easily implemented using a low-cost digital camera and specialized software called “Mic-Mac,” which provided data on the movements and deformations of visible portions of the structure. The basic concept involved installing the camera on an invar perch, equipped with a GPS system, to capture data at regular intervals that would be transmitted to a central database. An alarm would be triggered if any deflection or movement of selected points on the structure exceeded predefined thresholds. Structural engineers were responsible for identifying these critical points and setting the parameters for when the alarm should be activated to trigger an inspection or urgent action. A correct identification of these thresholds cannot rely solely on a traditional FE model. It must also be representative of reality. In fact, when aiming for cost-effective monitoring and when data on the materials used during construction are unavailable, a level of knowledge 1 (KL1) is assumed. This also means that in-depth analyses in terms of geometry and/or material performance are not conducted, often for economic reasons. The standards [48] permit this type of assumption, provided that more stringent safety correction factors are applied during analysis. Therefore, an optimization process is necessary to develop an efficient predictive model (FEM_U), as outlined in the schema in Fig. 15.

For this purpose, differential evolution (DE) algorithm can be used. It is a direct parallel search method designed for large-scale optimization problems [53]. Various applications of this algorithm can be found in Literature, such as the identification of dynamic parameters of a structure to update a FE model. With this objective, Bassoli et al. utilized a calibration process based on an improved surrogate-assisted evolutionary algorithm called DE-S [54,55]. This algorithm combines the robustness of the Differential Evolution algorithm [53] with the computational efficiency resulting from the second-order surrogate approximation of the objective function [56,57]. In bridge engineering, DE serve various purposes, primarily involving the optimization of bridge performance [58,59] and the refinement of bridge maintenance plans [60].

As depicted in Fig. 15, a simplified model identifies objective functions and optimization parameters, while target values are determined through in-situ vertical deflection measurements. Utilizing three technologies—two traditional methods and DIC—the most cost-effective option.

The DE algorithm is then employed to optimize the parameters defined in the simplified model, which can subsequently be used to update the FE model. This process enhances the accuracy of structural

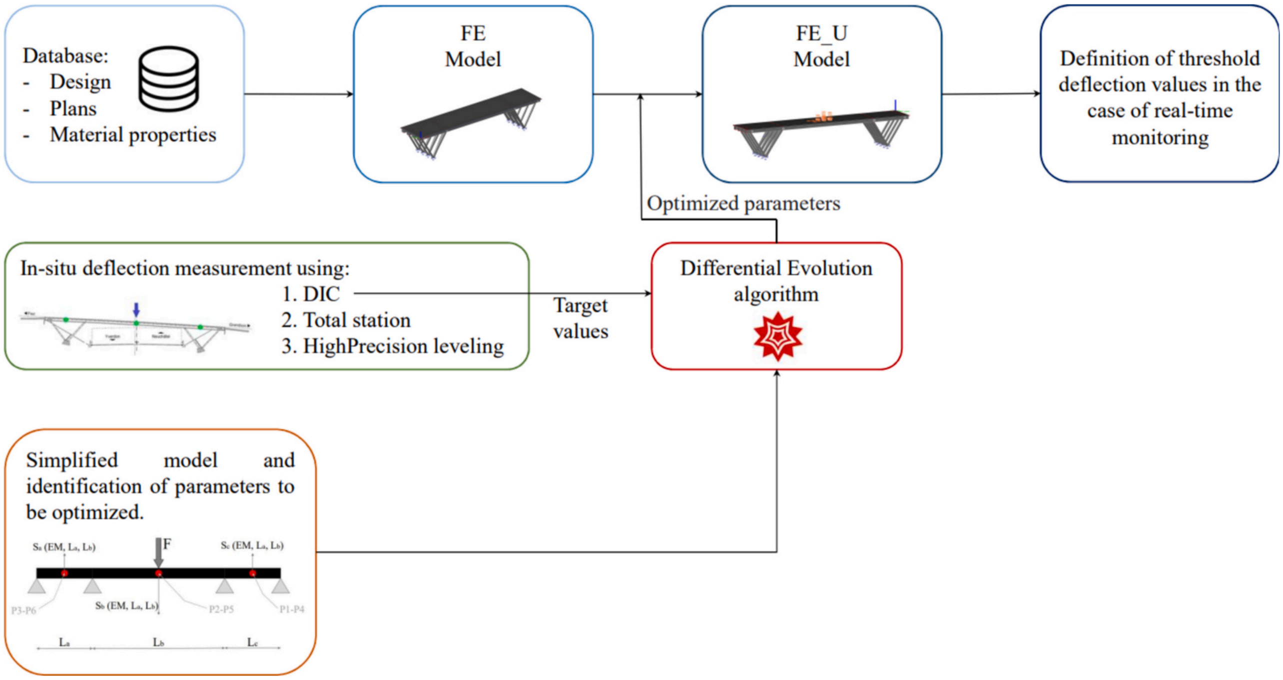

Fig. 15. Overview of methodology adapted for Grandson Bridge.

behavior predictions and establishes threshold values for deflection to identify anomalies in real-time monitoring. This procedure is particularly effective for small bridges, defined as those under 50 m in span. Otherwise, the parameters become too numerous for optimization based on a simplified model, making result control challenging.

This approach is subsequently applied to an existing bridge (Grandson Bridge), demonstrating both its potential and its limitations. On one hand, it highlights the capability to monitor smaller bridges with low-cost instrumentation. On the other hand, it reveals significant challenges related to the operation and updating of numerous single-purpose FE structural models, each constructed by different engineers using various software tools. This case underscores the need to update the approach to meet current demands by using interoperable DTs that facilitate direct monitoring of small bridge structures through cost-effective methods. It also highlights the critical importance of open and interoperable DTs that can evolve alongside the physical bridge, demonstrating how many existing monitoring and system identification methods could be effectively repurposed within this new framework.

4.2. General characteristics of the grandson bridge

The bridge studied is located in Grandson (481 m altitude) and establishes a junction of the main road of Fiez (RC 260) over the highway that connects Yverdon-les-Bains with Bienne. It is composed of three spans. Each bridge span is formed by four prefabricated and prestressed reinforced concrete box beams with a wheelbase of 2.61 m, connected transversely by a 16 cm concrete slab. Two different types of prestressing are executed: (1) by bonded tendons for the extreme spans and (2) by post-tensioning.

Beams are supported by eight V-shaped piles. The latter elements are connected each other at the base via direct foundation. Figs. 16 and 17 show longitudinal and transversal sections of the studied bridge.

Considering that its opening to traffic dates back to 1987, materials are classified and defined according to the standards of that time [61,62]. Table 3 presents the material properties of the bridge, which were deducted by considering both the design plans and calculation reports, as well as the constraints imposed by the prevailing regulations at the time.

4.3. Acquisition systems

The acquisition systems aim to measure the displacement field at a specific point under various loading conditions. This will define the target parameters for the optimization model. The load is applied by the passage of a truck (21.995 tons), and the measurements are taken when the truck is at the centerline in three different positions, as depicted in

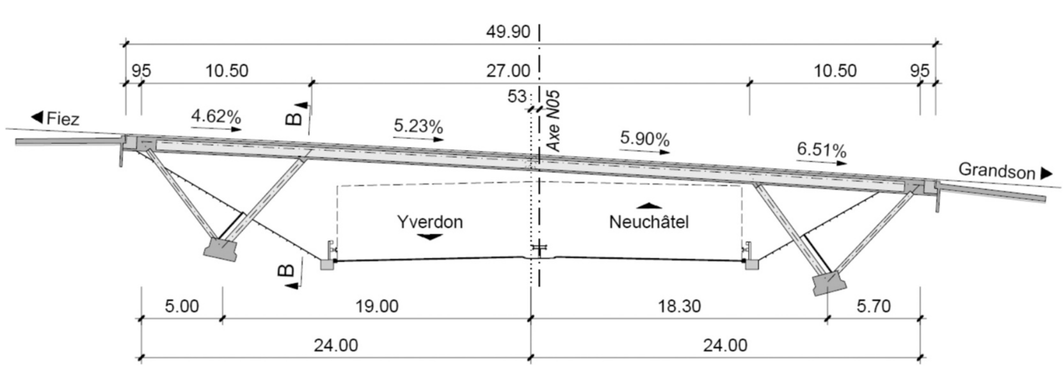

Fig. 16. Longitudinal section of the Grandson bridge.

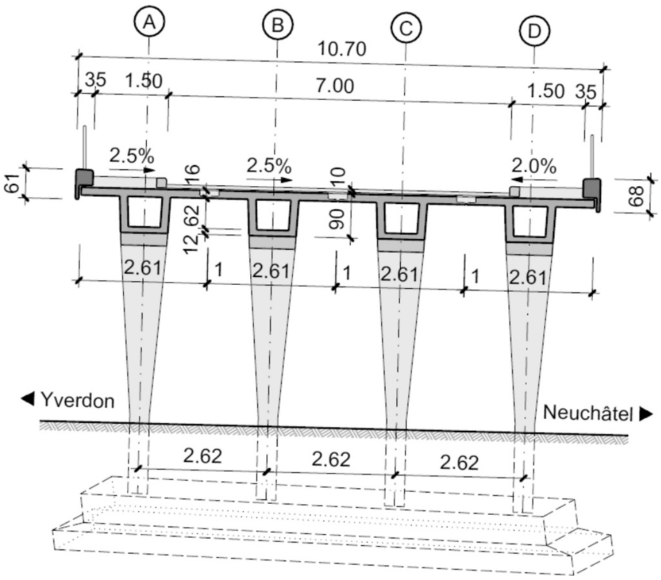

Fig. 17. Transversal section of the Grandson bridge.

Table 3
Material characteristics deducted from the standards of the time.

Element Type	$f_{cd,28}$ (MPa)	EM (MPa)	f_{yk} (MPa)	F_p (kN)	Regulation
Fondations	29.42	33,402	–	–	[61,62]
Piles	47.07	36,982	–	–	[61,62]
Bridge deck	47.07	36,982	–	–	[61,62]
Steel bars	–	–	450	–	[61,62]
Adherent wires	–	–	1500	44.52	[61,62]
Post-prestressed cables	–	–	1550	1255.25	[61,62]

$f_{cd,28}$: Design 28-days compressive strength; EM: Elastic Modulus; f_{yk}: Characteristic yield strength; F_p: Prestressing force.

Fig. 18. The geometrical characteristics of the truck can be found in Fig. 19. The load magnitude was chosen to ensure measurable deformations. Measurement points are positioned at the midpoint of the bridge, where deformations are greatest, thereby minimizing the impact of inherent measurement errors.

Three different technologies have been employed to measure the displacement field for three different load conditions: (i) high precision leveling, (ii) total station measurements and (iii) DIC.

The first two techniques were chosen for their widespread use in surveying, enabling measurement of vertical deflection and horizontal displacement. DIC was selected for its emerging reputation as a cost-effective solution. DIC involves analyzing digital images taken at different times to detect displacements using affordable cameras [63–66]. Despite being widely used in laboratories [67,68], a challenge is the impact of camera movement on measured quantities [69]. DIC has successfully monitored deformations in structures and studied degradation phenomena, including corrosion of rebars [70–72]. However, the use of some commercial DIC systems must be carefully evaluated when varying lighting conditions, occurs, since further algorithmic calculations might be necessary [73].

The leveling network was surveyed and included four control points (outside of the measurement area) using a digital level (NA03 by Leica Geosystems) and an invar staff to minimize any thermal deformations which could compromise the quality of the measurements [74], see Fig. 18. The displacement field is evaluated for each load combination at the labeled points P2 and P5 as reported in Fig. 18.

Two total stations (MS50 by Leica Geosystems) were installed outside of the measurement area on the northern side of the bridge in order to measure the points displacements, in which are placed the targets, see Figs. 18 and 20. Control points were used to check the stability of both, the digital levels and the total stations. This correction has been taken into account in Section 4.5.1.

The DIC technology is used to evaluate the entire vertical displacement of the bridge deck for both sides of the bridge. Images were captured by one Canon EOS 5D Mark III with 50 mm focal length. This device has been installed so as to remain as stable as possible between shots, see Fig. 21. Shooting parameters were set so as to obtain the best signal to noise ratio, with intensity levels close to saturation on the deck of the bridge. The arrangement of cameras and measured points of the three different technologies is shown in Fig. 18.

In order to know the pixel size of the DIC measurements, bridge length was measured with both techniques: total stations and DIC. The ratio between the number of pixels separating these two points in the

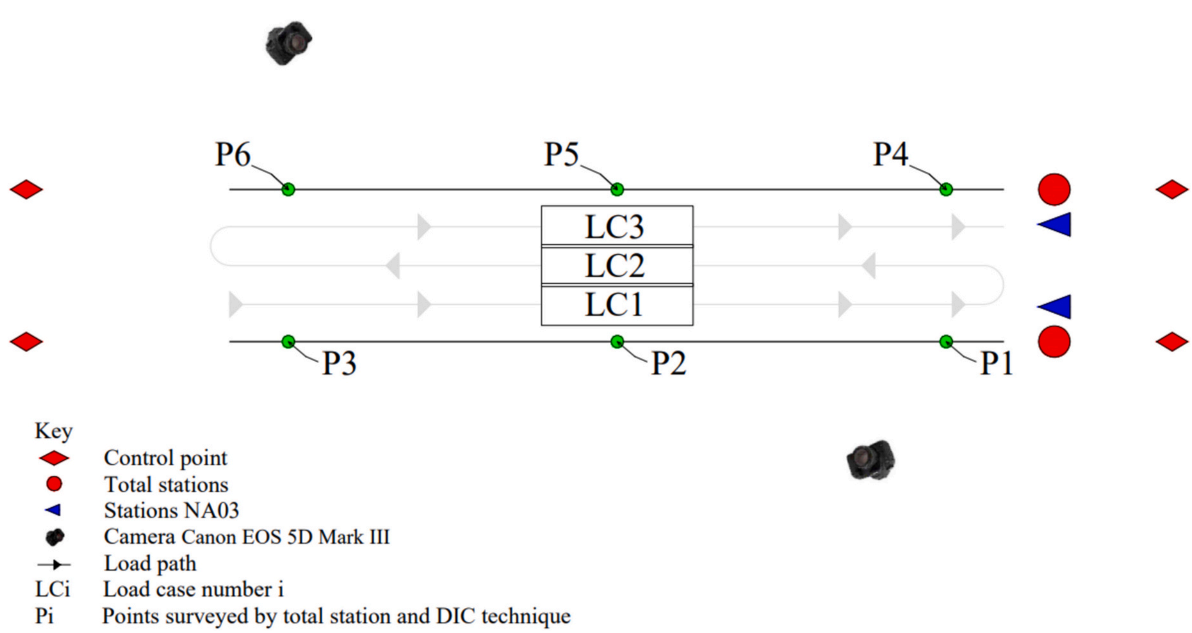

Fig. 18. Load case disposition and the set up for the surveying measurements.

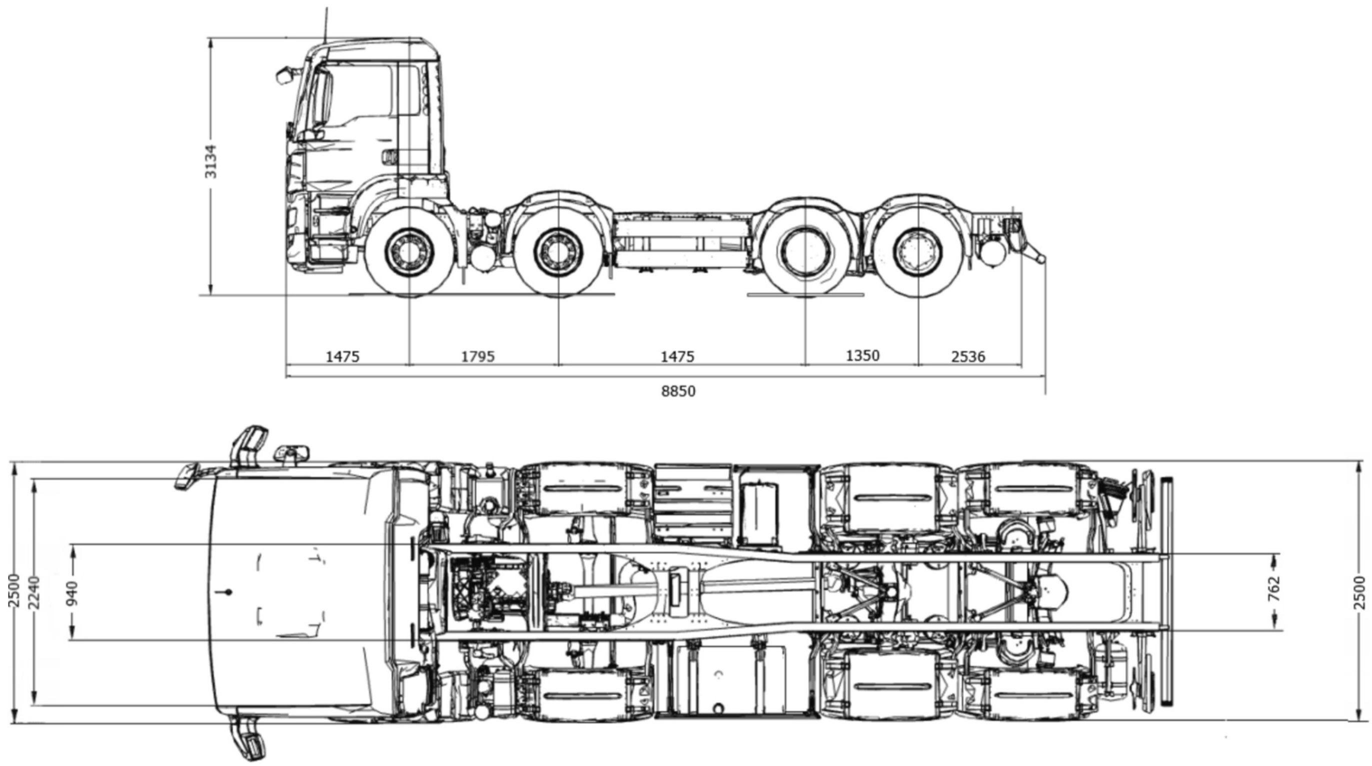

Fig. 19. Geometrical characteristic of the truck (dimensions in mm).

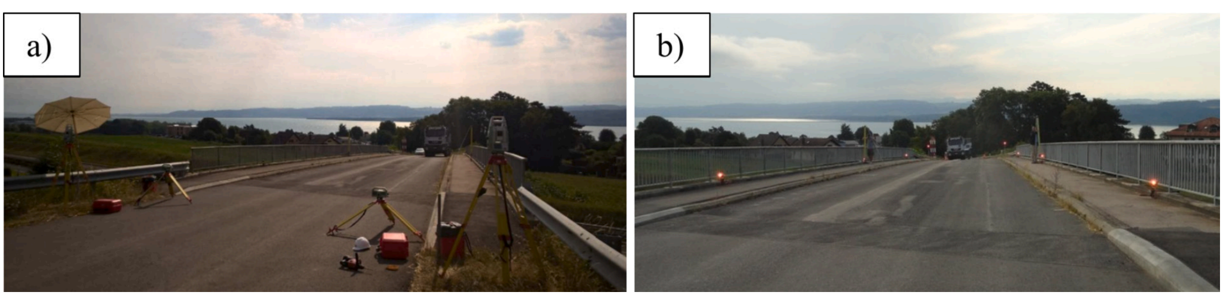

Fig. 20. a) Total station and digital level location, b) Target point location Pi.

Fig. 21. DIC measurements.

image and the metric distance returns the scaling factor. During the data processing a mask delimitation is made to evaluate the correlation, see Fig. 22. Correlation is made via an open source software "MicMac" [75], the main implemented correlation factors are reported in Table 4. In fact, points measured with the DIC refer to the mask and have been taken as close as possible in the position of the target points where receivers were located (see Fig. 18). The precision achieved is of the order of 0.01 mm.

The visualizations were performed with the SAGA GIS software [76]. A translation of the second image has been undertaken for several steps, as it is often observed that both images experience slight shifts of up to 5 pixels. Translation values are resulting from the Helmert calculation. This provides a homogeneous translation, a factor scale and a rotation between the reference image and the distorted one, see Eq. (1)

$$P = sQR + \iota T^T \tag{1}$$

where

$$R = \begin{bmatrix} 1 & \theta_3 & -\theta_2 \\ -\theta_3 & 1 & \theta_1 \\ \theta_2 & -\theta_1 & 1 \end{bmatrix}$$

Fig. 22. Mask definition for the correlation evaluation.

Table 4
Implemented correlation parameter.

Parameters	Settings
Correlation window size	10 plxs
Minimum correlation coefficient	0.98
Correlation range	0.02–1 plxs
Regularization coefficient	0.01

s is the scale factor, $R \in R^{3\times3}$ is a rotation matrix, ν is an n-length vector and T is $R^{3\times1}$ translation matrix. Translation correction provides regular results; in fact, this solution is preferred instead of modifying the calculation parameters between different images in pairs.

4.4. Finite element model (grandson bridge)

A Finite Element (FE) model of the Grandson bridge was manually created, with SCIA Engineer software [47], in order to compare the acquired results with those extracted from the structural analysis. It can be observed that, in comparison to the previous case study (see Section 3.5), the absence of interoperability or an existing DT imposes a significant constraint on modeling efficiency. Indeed, although the Praz Bridge case required some manual operations, these were minimal.

The FE model is compliant with the geometric characteristics reported in Figs. 16 and 17 and calibrated accordingly to the materials parameters reported in Table 3. The piles are modelled as 1D-beam elements. Both, the caisson beams and the slab, are modelled through 2D shell elements that are subjected to an average size mesh refinement of 250 mm. A fixed constrain condition is applied at the base of the structure. This seems to be reasonable because of the foundations dimension. Fig. 23 shows the solid and the single-line FE model views.

The static load is modelled according to the trucks' technical specification, see Fig. 19. The total load of 21.995 ton is applied following an appropriate distribution: each wheel is considered to have a load footprint of 40 × 40 cm. A further load sharing is made by following an inclination of 45° until the slab half thickness [48], see Fig. 24. Fig. 25

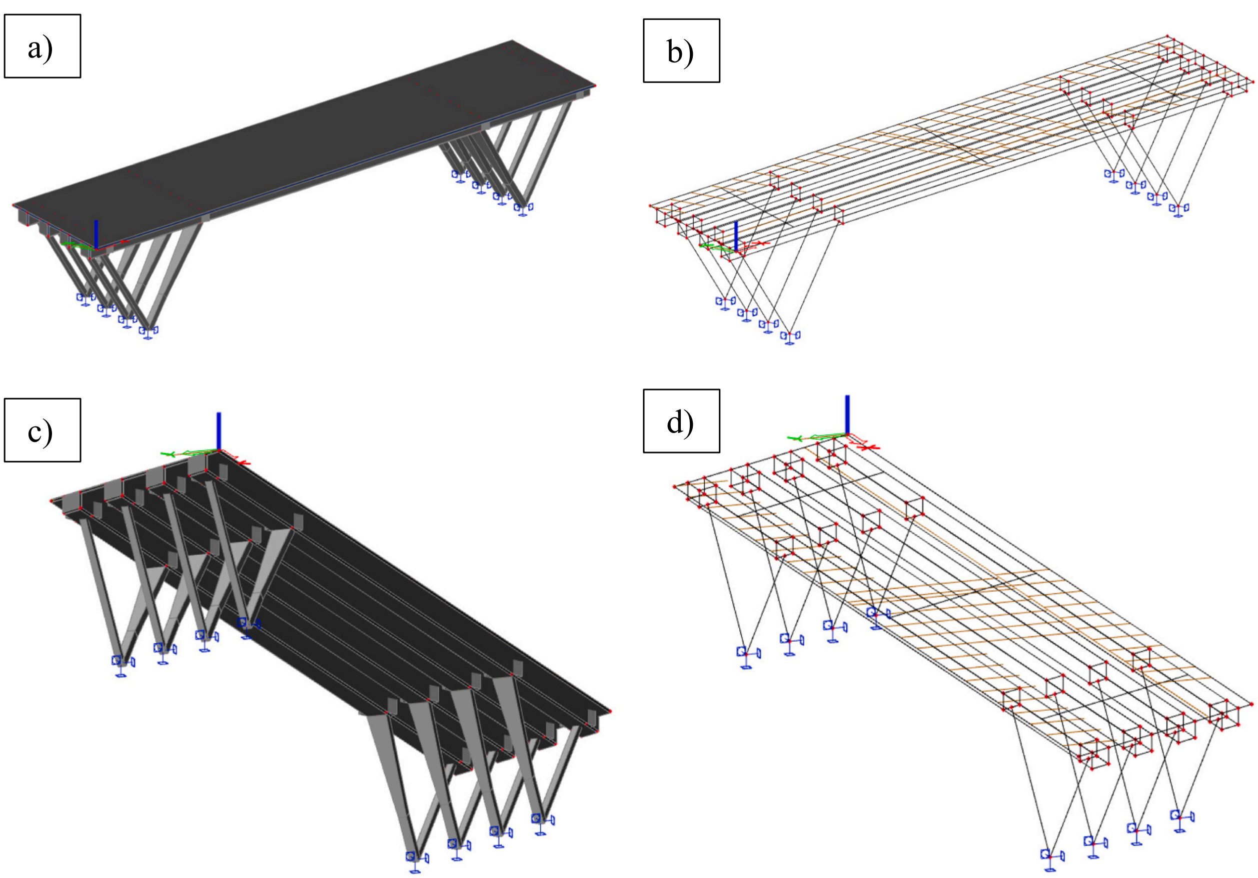

Fig. 23. FE model (Grandson bridge): a) solid view from the top, b) single-line view from the top, c) solid view from the bottom, d) single-line view from the bottom.

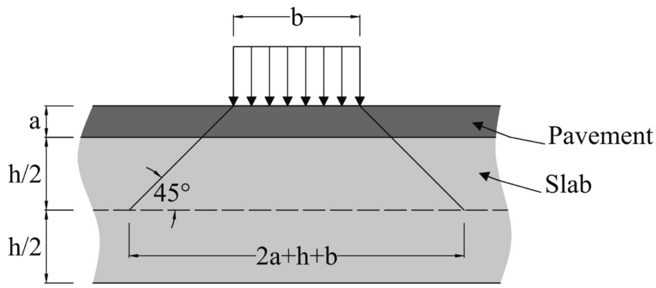

Fig. 24. Load diffusion in a slab [48].

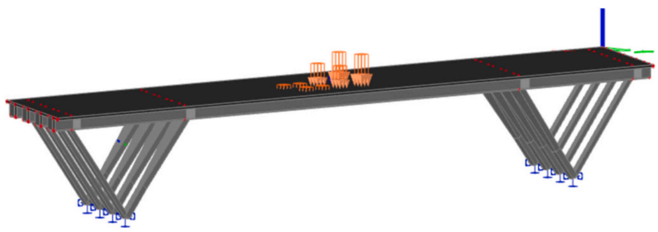

Fig. 25. First load case (LC1).

reports the first load case disposition.

Although this model respects the dictates of the time, it does not represent faithfully the real stiffness, the geometries, and the materials used. Such differences lead to results that render the predictive model unsuitable for monitoring purposes. This can be compensated by an optimization process.

In order to update the FE model, the problem is first simplified, leading to an optimized law while maintaining computational efficiency. The proposed approach relies on the static scheme illustrated in Fig. 26. Displacement values at points P1-P6, indicated in Fig. 26, were computed assuming the bridge deck as a Timoshenko beam element. The displacement functions S_a, S_b, and S_c have been expressed in function of: the (i) elastic modulus (EM), (ii) the first span length (L_a), and (iii) the middle span length (L_b). These are the key variables to be optimized. According to [77], optimization parameters might include material characteristics, geometric features, and masses. The EM was chosen for its significant influence on the entire structure, along with L_a and L_b for taking into account potential asymmetries. L affects deflection with a power of 3, while self-weight, EM and inertia with a power of 1. Notably, not all software allows inertia variation without altering the cross-section. The DE algorithm implemented facilitates escaping local minima, but the optimized solution may deviate significantly from initial values if parameters that strongly impact control parameters (S_a, S_b and S_c) are not used. However, optimization parameters choice also depends on the model's objectives and the structure type. The DE algorithm is implemented in Wolfram Mathematica platform [78]. The optimization process entails minimizing the objective function, obtained as the sum of squared differences between measured (mean of DIC measurements for all loading conditions for each midspan) the

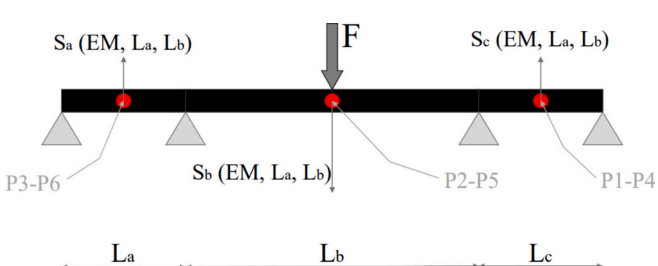

Fig. 26. Simplified static diagram for the FE model optimization.

calculated values using the displacement functions S_a, S_b, and S_c.

4.5. Digital twins vs. outdated bridge models: Insights from the grandson bridge example

The subsequent sections detail the results of an updated finite element model (FEM_U) developed for monitoring purposes. Although this model accurately reflects the bridge's condition at a specific moment, it does not include periodic updates necessary to capture the ongoing progression of bridge degradation. Consequently, an additional section explores the application of DT for real-time monitoring, utilizing models from existing Literature, to address the limitations of the outdated model.

4.5.1. In-situ measurements

Initially, the results from in-situ measurements are presented to: (i) validate the accuracy of DIC as a displacement measurement tool, and (ii) establish reference parameters for calibrating an optimized FE model.

A comparison between the displacements measured by the three different acquisition systems is reported in Fig. 27. For the sake of clarity the acronym LCi TS/DIC/L refers to the i-th load case (LCi), for the respective technologies of Total Station (TS), Digital Image Correlation (DIC), and high-precision level (L).

From the two digital levels (NA03), displacement measurements were made on both P2 and P5 and the deviations between the initial and final discharge condition calculated. These differences are used to compensate the measurements.

It is possible to note that the discrepancies between the observed values are acceptable, in particular when considering those obtained using the DIC method. This is due to the fact that the DIC measurements are taken on the bridge deck, which does not have precisely the same measured points as other methods, even if they are very close. It should be noted that the downward displacements have a negative sign. These results suggest how the use of a cost-effective technology like DIC can be easily employed for monitoring small structures, while still achieving a good approximation of the measured results.

4.5.2. FE model optimization with DIC measurements

Starting from the average DIC displacement results for each midspan the optimization of the FE model has been made manually using the DE algorithm to determine the global minimum of the objective function obtained as described in Section 4.4. To ensure physically meaningful solutions, the values of L_a and L_b were constrained between 9 and 12 m and 26 and 30 m, respectively. After multiple iterations, the optimal values of EM, L_a, and L_b were obtained as 67,432.7 MPa, 9 m, and 30 m. In Fig. 28, the iterative process followed to determine the most suitable parameters is depicted.

Fig. 29 presents the comparison between the results of the non-optimized model (FEM), FEM_U, and DIC vertical deflection measurements. It is possible to observe that displacements calculated using the non-optimized model are significantly larger, reaching up to three times the DIC values measured. This implies that compared to conventional modeling the reality appears to be much stiffer. This is caused by a combination of two factors: (i) the materials effectively used were more performant than those declared (this has a direct influence on EM used) and (ii) the model does not consider the rigidity offered by some non-structural element such as the pavement and the curbs. Instead, the FEM_U accurately captures the DIC measured displacements with average low errors.

These turn out to be suitable for the purpose, mainly because a simplified model with few variables was utilized to achieve computational efficiency in the optimization of the FE model. The points with the smallest error are prime candidates for sensor placement in potential real-time monitoring systems. In Fig. 30, a schematic illustration of the midspan displacement values obtained through DIC, FEM_U and FEM is

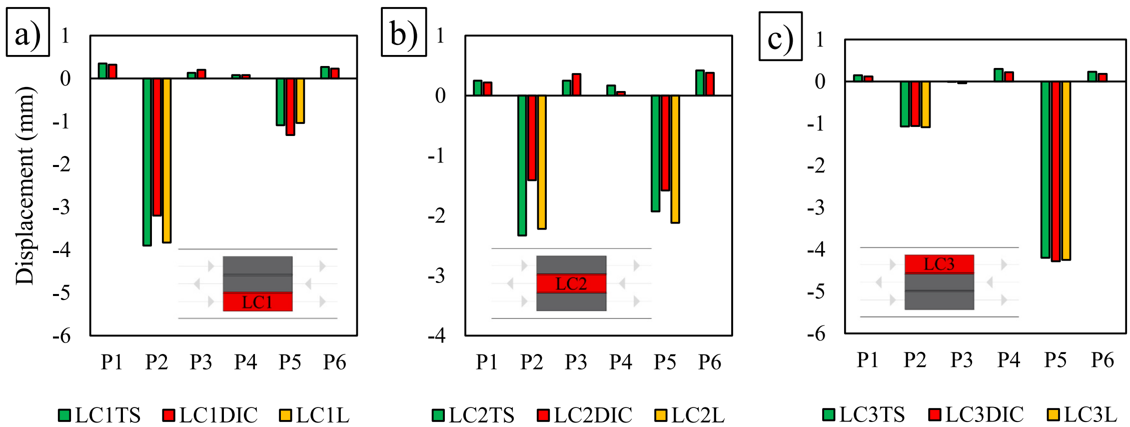

Fig. 27. Comparison of midspan displacements measured by different techniques for: a) LC1, b) LC2, and c) LC3.

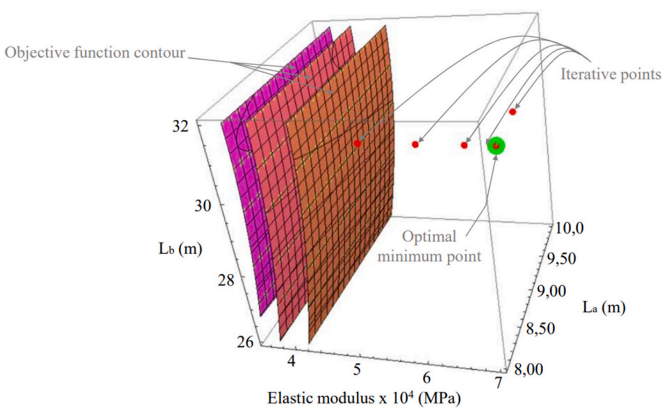

Fig. 28. FE model updating process through the differential evolution algorithm.

shown. The deformations were obtained using interpolation laws. The percentage deviations are referenced to the DIC measurement, serving as a comparative benchmark. A certain asymmetry can be observed both longitudinally and transversely. This aspect was already captured by the non-optimized model, highlighting the appropriateness of the geometry implemented in the FE model even in the absence of a scanning survey. Nevertheless, by using L_a as an optimization parameter, FEM_U allows to better capture the longitudinal asymmetric behavior. Instead, the transverse behavior was not considered in the optimization process since the optimization function was written for a beam Timoshenko element.

To achieve better accordance, the optimization function should be based on bending plates solution, taking into account the deformability of the V-shaped piles, and considering more optimization parameters. However, this would result in a significant increase in computational effort, compromising the cost-effectiveness aim.

4.5.3. Leveraging DT and optimized FEM for teal-time monitoring

At present, the data from this case and the prepared model could be fully recovered only because the software developers and FE model designers are authors of this paper or members of the same institution. Additionally, the version of the software used to construct the FE model is still available on the institution's servers. A competent engineer who did not participate in this research or who only had access to the dataset without the proprietary software would not have been able to retrieve the relevant information. Moreover, the bridge, which was recently refurbished at the time, may exhibit different behavior today, by instance due to degradation phenomena or geotechnical issues.

While this method is effective in the short term, it faces several challenges regarding long-term viability. Firstly, the issue of software obsolescence arises, as the software may become outdated or unavailable within a few years. Additionally, the model requires manual updates based on inspections conducted by specialized operators. In contrast, a DT similar to the one used for the Praz Bridge can mitigate these issues by: (i) offering interoperability and resistance to obsolescence, and (ii) facilitating more efficient model optimization through tools such as degradation visualization (see Figs. 10–11). Moreover, the DT interfaces with a system that leverages data from a cost-effective DIC system, which identifies abnormal displacements through image acquisition and measurement. This can be achieved by following a

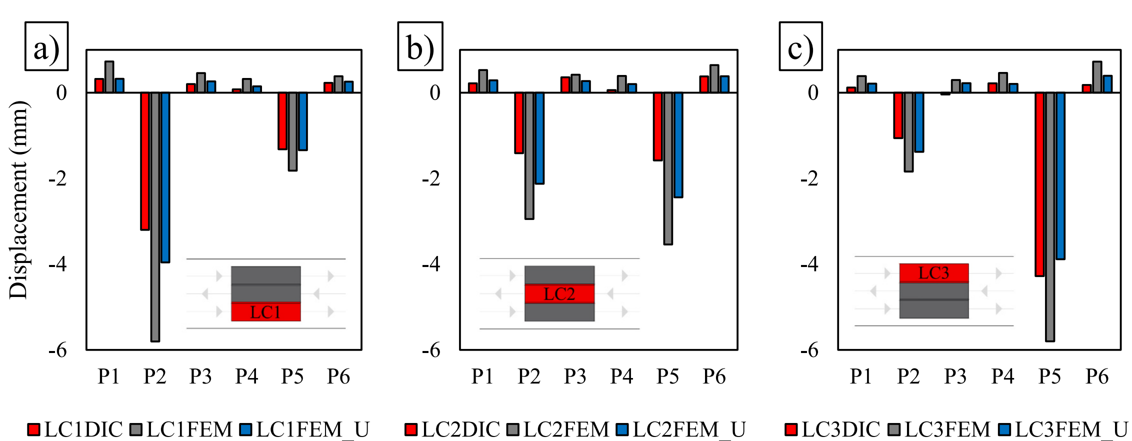

Fig. 29. Comparison of point displacements on the bridge deck for: a) LC1, b) LC2, and c) LC3.

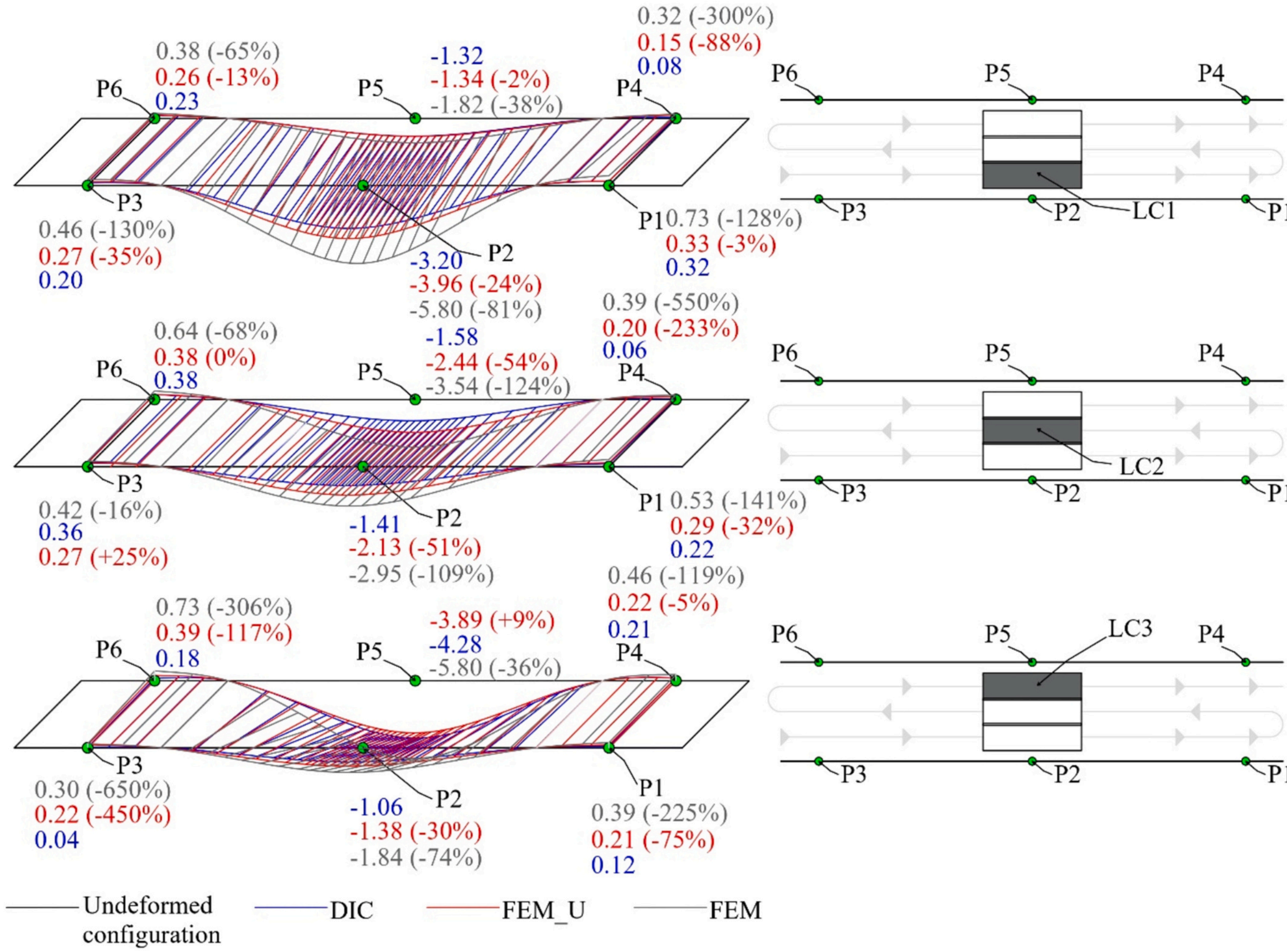

Fig. 30. Comparison of the deformed configuration evaluated with DIC, FEM and FEM_U for each load condition.

similar pattern to that presented in [36], see Fig. 31. In Phase 1, the FE model undergoes optimization using parameters defined by the DE algorithm. Various load combinations are applied to reach ULS [48], and permissible deflection values are established at critical points. In Phase 2, the predicted results are compared with field measurements under current conditions to assess changes in the target bridge object's condition.

This enables the transition to a DT at higher levels of maturity, as it has a direct real-time connection with the physical object and can inform inspectors immediately upon detecting an abnormal deflection.

Meanwhile, the DT, coupled with the continuous monitoring system, would enable inspectors to oversee a large number of structures without needing to move unless urgent or planned inspections are scheduled.

5. Conclusions and future work

This paper presents a comprehensive methodology for developing and utilizing Digital Twin (DT) models for existing bridges. Key elements of this methodology include the integration of Building Information Modeling (BIM), open-access interoperable formats, and a

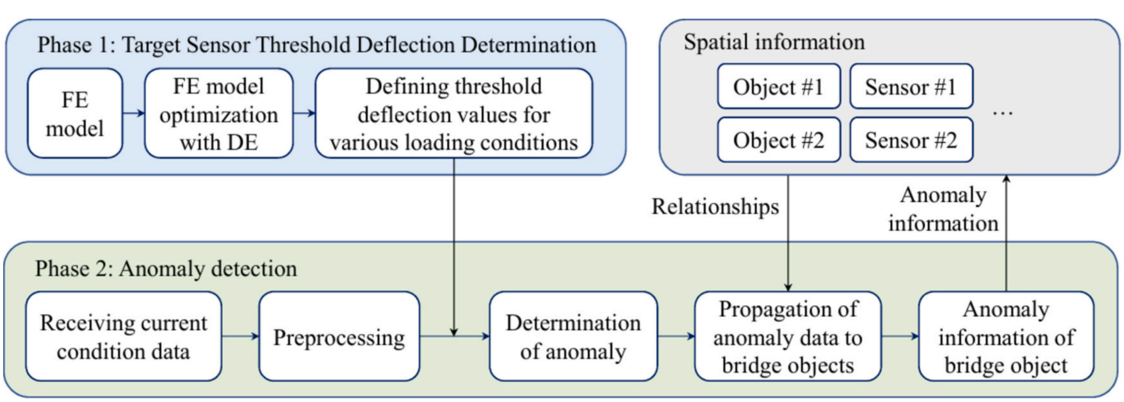

Fig. 31. Method for monitoring bridge elements using optimized FE model.

specific ontology. This approach ensures that DTs accurately reflect the current state of the bridge and can incorporate past and future inspections and monitoring results. It facilitates precise assessments of structural health and its evolution over time, enabling optimal management of maintenance operations. Additionally, the methodology promotes collaboration among professionals, aiding bridge owners in knowledge sharing, cost reduction, safety enhancement, and addressing the obsolescence typical of non-interoperable digital models.

Key findings of this paper include:

1. Existing Bridges: For medium and large bridges, converting a laser-scanned 3D model into a digital twin using Industry Foundation Classes (IFC) protocols is feasible and time-efficient, though not fully automatic. These DTs enable "what if" scenario analyses, supporting more strategic and sustainable maintenance decisions.
2. Importance of Ontology and Interoperability: The effectiveness of a DT for bridge owners depends on its ontology, interoperability, openness, and ability to integrate results from ongoing structural health monitoring. These factors ensure that the DT remains a valuable tool throughout its lifecycle and is not prone to obsolescence.
3. Sustainability: This methodology supports sustainability throughout the bridge's lifecycle by enabling data-driven planning for deconstruction, reuse, and recycling at the end of its service life. More precise management of maintenance operations and the evolution of structural health can increase the lifespan of a bridge.

Research is underway, and future work is planned to address the following challenges and enhance the impact of DTs:

1. Integration of Inspection and Monitoring Results: Often, bridge owners have internal departments and protocols to identify, classify, rate, group, and insert into a database the parameters and degradation factors that influence the structural health of a bridge. Therefore, incorporating these parameters into a newly created DT is as seamless and efficient as the internal organization managing these issues. A new method should be developed to collect and organize data in a way that ensures efficiency and accuracy.
2. Applicability to New Bridges and Structures: The strategies discussed for constructing DTs are likely to be applicable to new bridges and structures, optimizing sustainability-based design. To be effective, DTs must be used during the design phase by all professionals involved and must be able to compute emissions, energy consumption, and waste throughout the entire construction process, including the supply chain.
3. Integration into a DT Network: DTs built with this methodology can be integrated into a broader network, enabling effective management of interactions between the bridge and its environment. However, the concept of collaborating DTs is still the subject of intense research, and a debate on the level of automation to be allowed in a network of DTs has not yet surfaced.

In summary, this work represents a significant advancement in the digitalization of bridges within a "cradle-to-cradle" framework, with the potential to streamline life cycle management, address software obsolescence, and ensure optimal longevity of structures. While the proposed methodology for building bridge DTs has proven effective in simplifying structural health assessments and enhancing maintenance decision-making, further research is needed to maximize its impact, particularly by simplifying the integration of inspection and monitoring results into DTs. Future work should focus on extending this methodology to other applications, such as optimizing the environmental impact of new constructions during the design phase. Additionally, research is necessary to explore the potential of integrating similarly constructed DTs into a network, enabling the modeling of entire transportation corridors and the territories in which they are situated.

CRediT authorship contribution statement

M. Franciosi: Writing – original draft, Software, Methodology, Investigation. **M. Kasser:** Writing – review & editing, Validation, Supervision. **M. Viviani:** Writing – review & editing, Validation, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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