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Development of BIM-Based Digital Twin Model for Fatigue Assessment in Metallic Railway Bridges

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Abstract
The emerging Digital Twins have brought great revolution in the processes of monitoring and managing assets such as bridges. This work, which is part of a pilot project, aims to evaluate and simulate the fatigue behavior in metallic railway bridges (MRB) supported by a Digital Twin, which in turn is based on Building Information Modeling (BIM) capabilities. An integrated system based on appropriate software and consisting of three main modules (Input Module; Calculation Module; Output Module) is assembled. The current stage is promising, being possible not only to estimate the fatigue damage for different scenarios, but also visualize it and access other damage-related information.

Author Keywords. Digital Twins, Metallic Railway Bridges, Fatigue Damage, Building Information Modeling, Bridge Information Modeling.

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1. Introduction

Fatigue is one of the most common failure modes in steel structures (Santecchia et al. 2016), and in the case of Metallic Railway Bridges (MRB), it is mostly caused by repetitive loads induced by passing trains. The evaluation and monitoring of this phenomenon in the service stage has shown to not be easy, owing to its complexity, which has posed significant hurdles in the quest for strong tools and procedures to aid in the inspection and monitoring processes involving fatigue. The emerging Digital Twins (DTs) have the potential to revolutionize operation and maintenance (Leser et al. 2020) and can substantially assist in the management, inspection, and assessment of bridge behavior, including the fatigue. The evaluation of structural behavior using or aided by DT has currently been investigated, and it is a rapidly growing trend, which is obviously associated to the Industry 4.0 era (digitalization). Dong et al. (2021) and Ye et al. (2019) are two recent research to mention: Dong et al. (2021) developed a DT model to predict the fatigue life of a bridge-crane, where information such as loading and strain history and the working cycles of the bridge-crane were collected from the physical counterpart to feed the virtual model. In the work developed by Ye et al. (2019), concerning structural integrity monitoring, the authors present a discussion of two years of exploratory investigation concerning the building of the DT model, with a stronger focus on the capabilities required for the development of that model.

It is widely known that although some developments related to DTs are already a few decades old, DTs as such and especially as a concept are still in their infancy (Liu et al. 2021) and their application and research in the Architecture Engineering and Construction (AEC) sector is still much more recent, with few practical applications when compared to other sectors, such as the manufacturing sector. The concept of DT was first introduced in 2003 (Grieves 2014) and only in 2011 the first journal article was published (Tao et al. 2019). In the AEC context it is quite common to associate DT model with Building Information Modeling (BIM) (Boje et al. 2020) or Bridge Information Modeling (BrIM) in the case of bridges, as there are some aspects in common between these models. However, since DTs are still in their early stages and there are no regulations or standards covering all fields, many aspects remain open. Some research on DTs is not very clear regarding for example to the software and communication processes between physical and digital entities, mainly from the point of view of practical implementation. Regarding software, there are so-called "closed source software (CSS)", generally commercial and predetermined to perform specific tasks, and so their use for DT (or similar models) are generally limited to combination with other software or applications for the intended purpose, with incompatibilities between the software/applications posing possible limitations. On the other side, "open sources software (OSS)" are open to a variety of applications and modifications, however, depending on the intended purpose, their use may be too complex.

The purpose of this study is to describe the methodology and show the first steps of DT model development for fatigue assessment of existing MRB in a global and conservative standpoint. BIM capabilities are used to support the model and an integration of tools/software with enhanced capabilities for fatigue damage computation is performed. This enables the creation of a model with three modules, namely the Input module (Module I), the Calculation module (Module II) and the Output module (Module III). Module I includes the digital copy of the bridge and other stored information required for fatigue assessment collected on the physical twin (physical bridge); in Module II, the fatigue is calculated for scenarios related to the information available in Module I; finally, Module III integrates Module II and the digital copy created in Module I, allowing graph visualization of the fatigue damage and information related to this damage, simulation for different scenarios and continuous updating of the model.

2. Theoretical approach

2.1. Digital Twin paradigm

In the increasingly digital world, DTs have been a great bet for the improvement of systems or support in processes to solve various problems in different fields. Although some developments related to DTs are already a few decades old, DTs as such and especially as a concept are still in their infancy (Liu et al. 2021). The concept of DT was first introduced in 2003 by Michael Grieves in a course on product life cycle management at the university of Michigan (Grieves 2014) and only in 2011 the first journal article was published (Tao et al. 2019).

Currently there are several definitions and understandings of DTs, and there are still no standards or regulations covering all sectors. The manufacturing industry, for example, is more advanced and has already some standardization, as seen by the recent publication of ISO 23247-1:2021 ("Automation systems and integration - Digital twin framework for manufacturing - Part 1: Overview and general principles") (ISO 23247-1 2021). Currently, in the AEC sector the creation of DT does not follow a specific standard or regulation in general, and in this sense other normative have been used where applicable, including, for example, the standards and guides applied for BIM, since for the AEC sector there are some aspects in common between DTs and BIM.

As previously stated, there are several definitions and understandings of DT. Within these varieties, a DT can be defined as being a virtual representation of a physical asset, system, or process (physical twin), which can be updated in real-time or near real-time as new data are collected, provide feedback to the physical twin, and simulate various scenarios to assess possible risks and predict the performance of the physical contrapart (Ye et al. 2019). Figure 1 basically illustrates this concept. The definition of a DT model's architecture is one of the criteria that govern its design. The physical part, the virtual portion, the connectivity between the physical and virtual parts, and the data are the general components that make up this design. The type of a model, as well as the field of application will determine the specific components of the architecture, such as aspects related to sensing, internet of things (IoT), artificial intelligence (AI), etc.

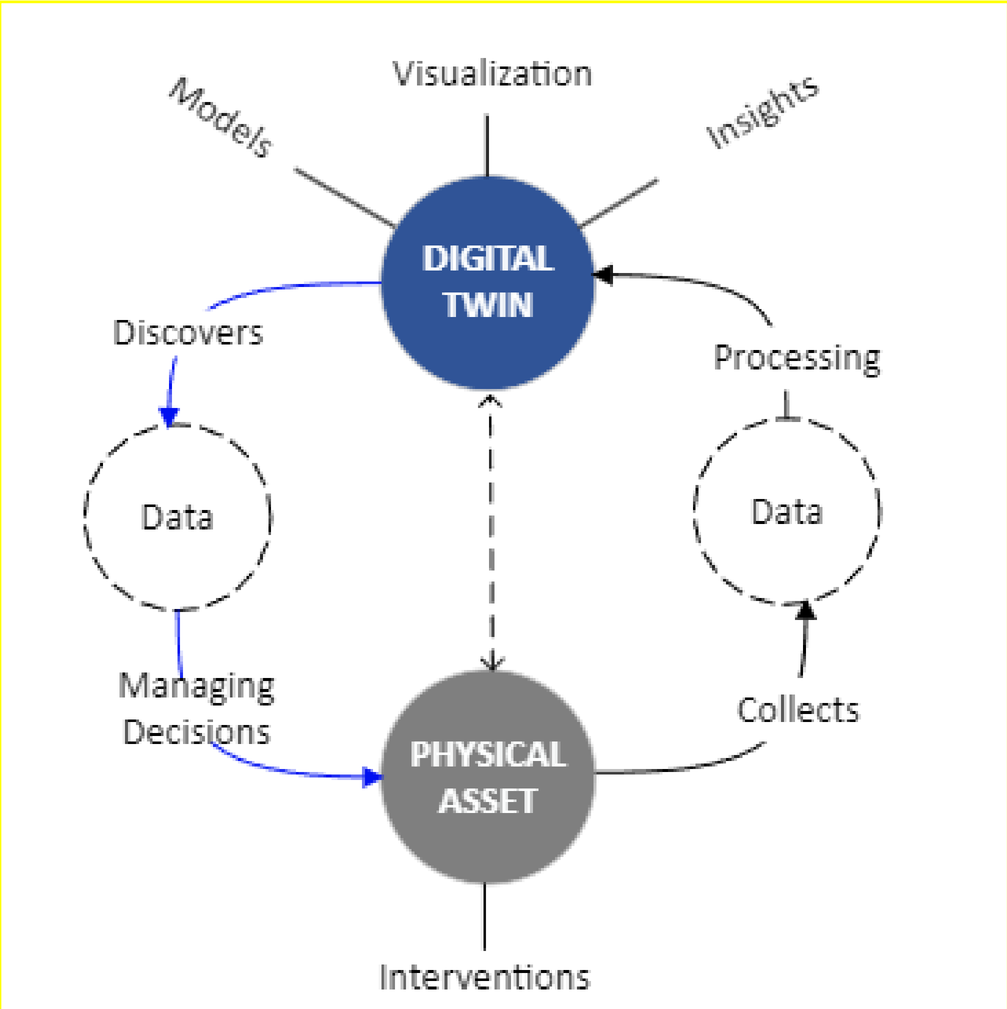

Figure 1: Basic concept of the Digital Twin (adapted from Boje et al. 2020)

Although the basic architecture is basically the same in most domains, a DT for the field of AEC will consider tools and technologies different from those applied for example in the manufacturing sector (Boje et al. 2020). (Madni et al. 2019) propose categorization of DT into four levels based on the model's sophistication or maturity: Level 1 - pre-digital twin, Level 2 - digital twin, Level 3 - adaptive digital twin, and Level 4 - intelligent digital twin.

The description of these levels is presented in Table 1.

Level	Model Sophistication	Physical Twin	Data Acquisition From Physical Twin and Connectivity	“Machine Learning” (System/Environment)
1 Pre- digital twin	virtual system model with emphasis on technology/technical-risk mitigation	does not exist	Not applicable	no
2 Digital twin	virtual system model of the physical twin	exist	performance, health status, maintenance; batch updates/near real-time updates	no
3 Adaptative digital twin	virtual system model of the physical twin with adaptive user interface	exist	performance, health status, maintenance; real-time updates	no
4 Inteligent digital twin	virtual system model of the physical twin with adaptive user interface and reinforcement learning	exist	performance, health status, maintenance, environment; both batch/real-time updates	yes

Table 1: Levels of Digital Twin (adapted from Madni et al. (2019))

One of the characteristics of levels iii and iv is the transmission of data or the updating of the model in real time, which is an important aspect with regard to the communication between the physical and virtual parts.

From a temporal standpoint, (Shao and Helu 2020) distinguishes three types of communication between these two parts: real-time, near real-time, and offline communication. The last two occur when the updating of the virtual part is periodic, being for the near-real-time, shorter periods and the offline, relatively long periods.

Another classification concerning DTs is suggested by Errandonea et al. (2020), which according to the form of data transmission between the physical and virtual parts (interaction between the two parts), classifies the models into three categories: (i) Digital model - when data transmission between the two parts is manual; (ii) Digital shadow - when data transmission from the physical part to the virtual part is automatic and in the reverse direction manual (automatic unidirectional) and (iii) Digital twin - when data transmission between the two parts is automatic (automatic bidirectional).

These classifications, which are still under discussion among researchers, have heightened the need for attention on what to designate a DT, as well as the relevant aspects for the design of a particular level of DT. In AEC, it is common for DT to be associated with BIM (BrIM in the case of bridges) or use of part of the technologies used in BIM, and in these cases, BIM can be considered as a starting point for the creation of DT (Boje et al. 2020), where the BIM model is enriched, for example, with data from sensors, the IoT, in order to meet certain applications.

2.2. Fatigue analysis methodologies

Two methodologies proposed by the Eurocodes for the calculation of fatigue damage in connections: (i) Equivalent constant amplitude stress method and (ii) Accumulated linear damage method.

The equivalent constant amplitude stress method, also known as λ-coefficient method (Horas 2021), is a simplified method for fatigue assessment, based on stress ranges of standard loads.

This method is only suitable in cases where dynamic analysis is not required, considering in this case a quasi-static analysis for applicable loading models and adopting the appropriate dynamic amplification factors. The verifications entail meeting the following criteria, taking into consideration normal stress verification (1), shear stress verification (2), and simultaneous normal and shear stress verification (3):

$$\frac{\gamma_{Ff}.\ \Delta\sigma_{E2}}{\Delta\sigma_c/\gamma_{Mf}} \leq 1.0 \tag{1}$$

$$\frac{\gamma_{Ff}.\ \Delta\tau_{E2}}{\Delta\tau_c/\gamma_{Mf}} \leq 1.0 \tag{2}$$

$$\left(\frac{\gamma_{Ff}.\ \Delta\sigma_{E2}}{\Delta\sigma_c/\gamma_{Mf}}\right)^3 + \left(\frac{\gamma_{Ff}.\ \Delta\tau_{E2}}{\Delta\tau_c/\gamma_{Mf}}\right)^5 \leq 1.0 \tag{3}$$

In above equations, $\Delta\sigma_c$ e $\Delta\tau$ represent the fatigue resistance associated to 2 million cycles derived from the well-known S-N curve (Stress vs. number of cycles to failure), γ_{Mf} and γ_{Ff} represent the partial safety factors (part of the resistance and part of the action respectively) and, $\Delta\sigma_{E2}$ and $\Delta\tau_{E2}$ express the equivalent constant amplitude stress also associated to 2 million. In turn, the stresses $\Delta\sigma_{E2}$ and $\Delta\tau_{E2}$ are determined taking into account the (4 and (5 below:

$$\Delta\sigma_{E2} = \lambda.\Phi.\Delta\sigma_{71} \tag{4}$$

$$\Delta\tau_{E2} = \lambda.\Phi.\Delta\tau_{71} \tag{5}$$

where λ is equivalent damage factor, $\Delta\sigma_{71}$ and $\Delta\tau_{71}$ the maximum stress variations derived from the load models LM71 or SW/0 (if applicable) and Φ is the dynamics amplification factor, as defined in EN 1991-2 (CEN 2003).

The accumulated (use linear damage accumulation) linear damage method, also known as the Palmgren-Miner rule, is the most widely used in civil engineering and is more comprehensive if compared to the previous constant amplitude equivalent stress method. In this method the various acting stress amplitudes are not replaced by an equivalent amplitude and it can be considered either dynamic or quasi-static analysis considering real traffic or standard traffic which correspond to fatigue trains.

Briefly, the method works as follows: After applying the loads and determining the nominal stress at a detail for each loading interval, the S-N curves are applied to determine the number of cycles, n_i corresponding to each stress variation, $\Delta\sigma_i$ of the loading set, followed by the implementation of the accumulated linear damage, according to the following expression (6):

$$D = \sum \frac{n_i}{N_i} \leq D_L \tag{6}$$

where D denotes the fatigue damage accumulation considering a certain cyclic loading and n_i denotes the number of cycles for stress variation, $\Delta\sigma_i$, N_i denotes the fatigue life in cycles for the detail subjected to the same stress variation, and D_L denotes the damage limit (usually limited to 1).

The two approaches previously presented are considered conservative and more appropriate for global analysis, with the analysis based on nominal stresses (stress adjacent to the potential location of a crack, calculated through elasticity theory, excluding any effect of stress concentration (CEN 2010)) A comprehensive fatigue assessment process, on the other hand, entails several stages, beginning with preliminary analysis to identify fatigue-prone details, followed by more detailed evaluation (local evaluation and consideration of stress concentration), and finally a decision on possible interventions. Helmerich et al. (2007) and (Horas 2021) consider a four-phase sequence for complete fatigue assessment of existing steel bridges: phase I - preliminary assessment, phase II - standard assessment, phase III - detailed analysis and phase IV - critical decisions. The first two phases consider the application of the equivalent constant amplitude stress and linear damage accumulation methods, respectively. Phase III is a local and more advanced analysis, applied when phase II is not sufficient or not conclusive. In this phase, local, fracture mechanics and probabilistic methods are applied (Helmerich et al. 2007). Phase IV is related to decisions about interventions in the structure, taking into account the analyses involving the previous phases.

3. Methodology and model development

The proposed methodology for the development of the DT model covers three phases namely, the definition of the information requirements (EIR - Exchange Information Requirement), design of the framework, and model creation.

3.1. Information requirements definition

The definition of the information requirements, which is typical in BIM modeling and applicable to the DT model to be developed, is depicted next in Figure 2.

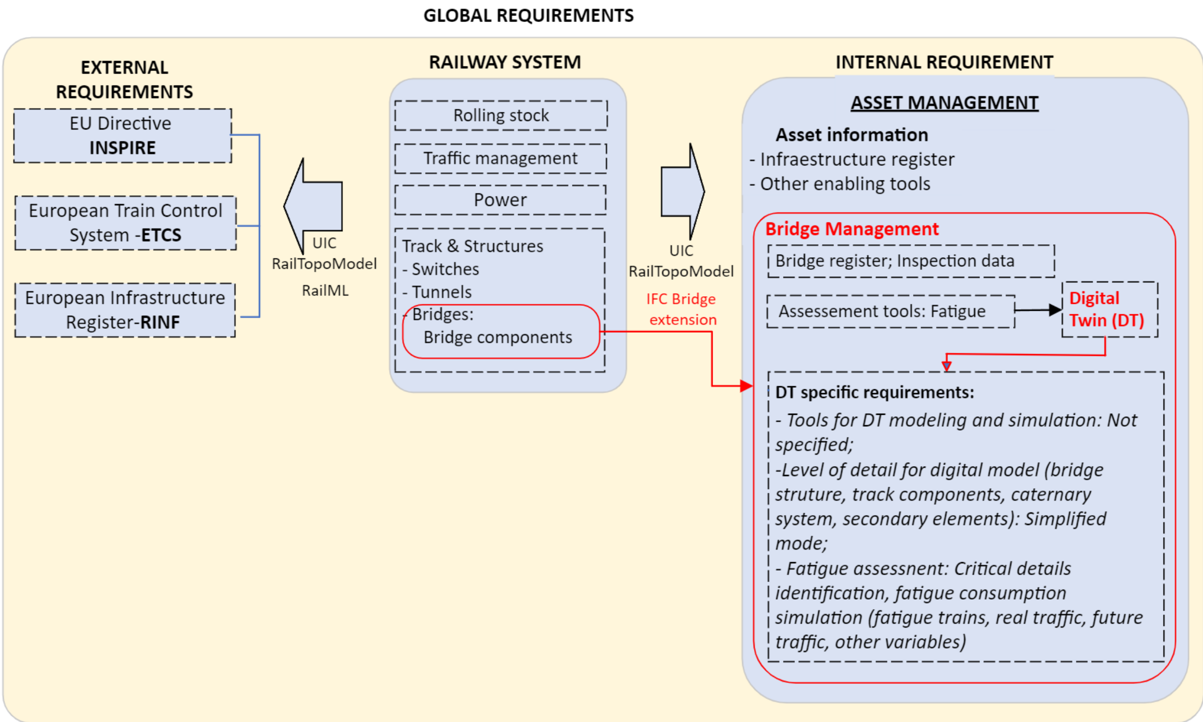

Figure 2: Information requirements definition

3.2. Global framework of Digital Twin model

The framework of the proposed DT model is presented in Figure 3. The model is developed using BrIM (Bridge Information Modeling - BIM for bridges) as the basis for managing the input information and results coming from the fatigue calculation tools.

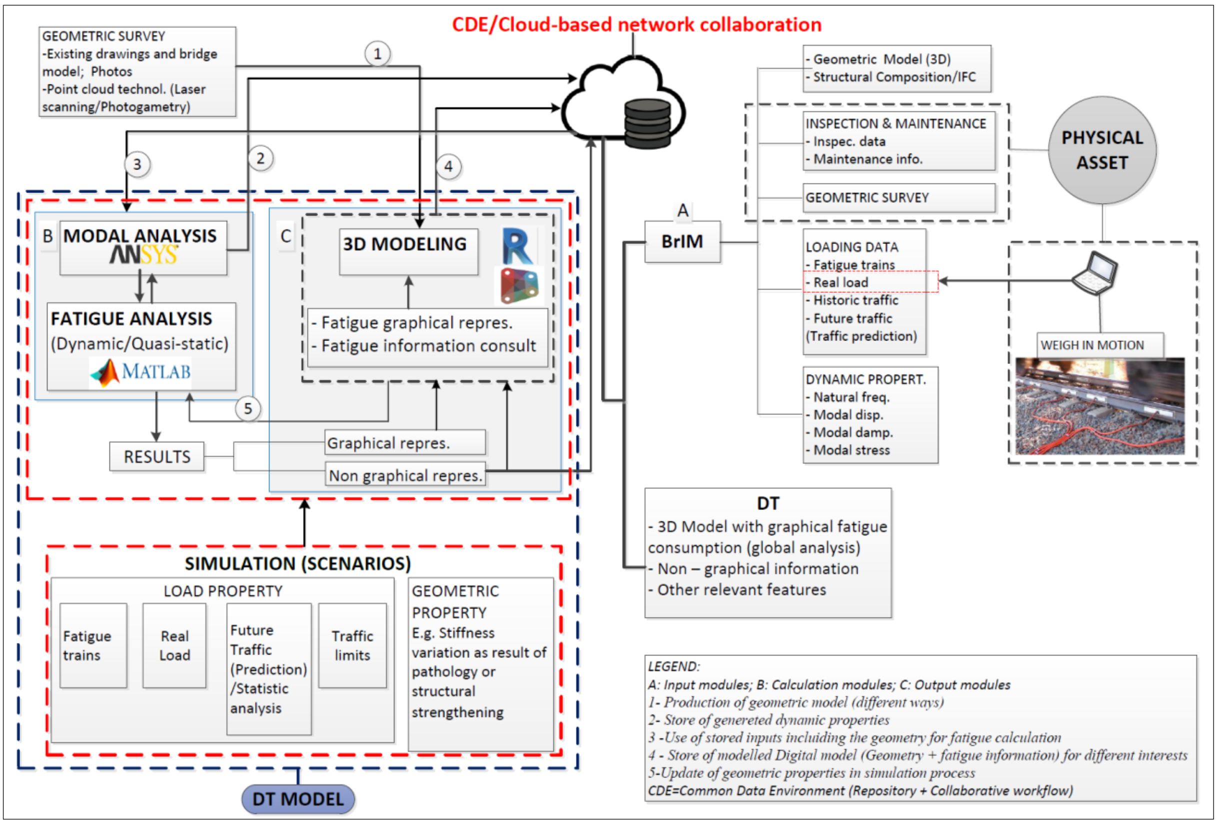

Figure 3: Framework of the proposed Digital Twin model

What fundamentally defines BrIM is a shareable and collaborative database containing relevant and necessary information for fatigue assessment, such as inspection data, dynamic properties of the bridge, rail traffic loads, and a three-dimensional geometric model of the bridge. REVIT® software (from California, U.S.), one of the most widely used packages for BIM modeling, is used to create the 3D geometric model of the bridge as well as the graphical visualization of the fatigue damage and the information related to such damage. A state-of-the-art conducted by Jiang et al. (2021) on the current state and trends of DTs in Civil Engineering, mentions REVIT® software as being at the top with regard to the means of digitizing the virtual part. The calculation of the fatigue damage considering the various scenarios is performed in MATLAB® software (from New Mexico, U.S.), and the necessary dynamic properties are calculated in ANSYS® software (from Pennsylvania, U.S.). This whole process allows the model to be divided into three modules, namely, input module, calculation module, and output module.

Input Module: The information contained in this module is stored in a cloud-based repository and is updateable in real-time by the different parties managing the model. For example, this module receives and stores traffic data from weigh-in-motion. Among the stored data, the module also receives the dynamic properties information processed in the calculation module.

Calculation Module: The calculation part is subdivided into two subparts: (i) the calculation of dynamic properties (modal analysis) in ANSYS® software (this is performed only once or whenever there are changes in the geometric properties of the structure) and (ii) the calculation of fatigue damage for different scenarios, in MATLAB® software.

Output Module: It consists of the fatigue damage results for various scenarios and the respective representation (graphical and non-graphical) in the bridge's geometric 3D model. The integration of the information in this module, coming from the calculation module and other information coming directly from the input module, is done through the API (Application Interface Programming) DYNAMO. The data coming directly from the input module is merely descriptive, such as the type of traffic considered for a given scenario, the identification of details, and so on. The Figure 4 depicts the entire integration process between the modules and associated software.

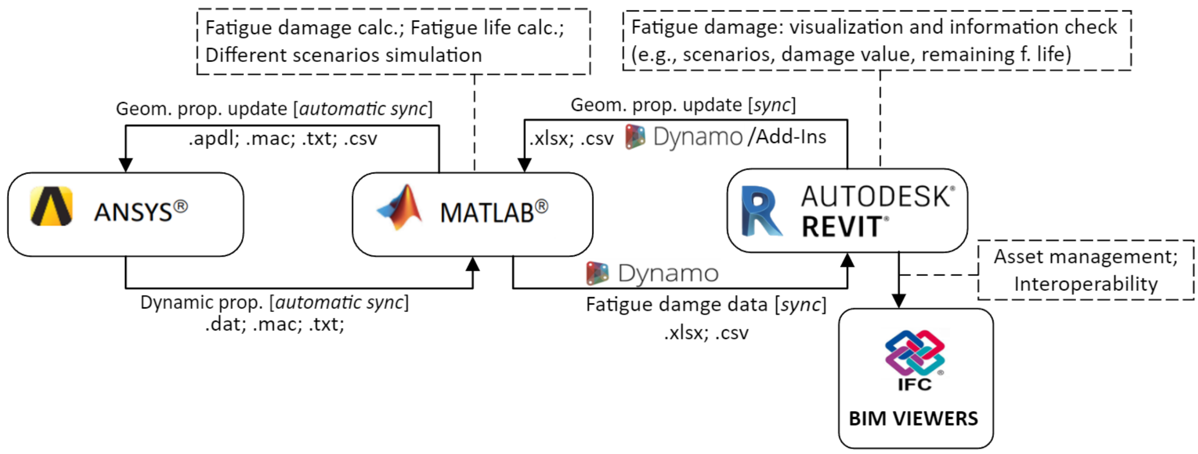

Figure 4: Integration process between modules or software/applications in the digital twin model

3.2.1. Fatigue damage calculation

The fatigue calculation is carried out using the methodology described in section 2.2, until level 2 (standard evaluation), and according to the procedure shown in Figure 5.

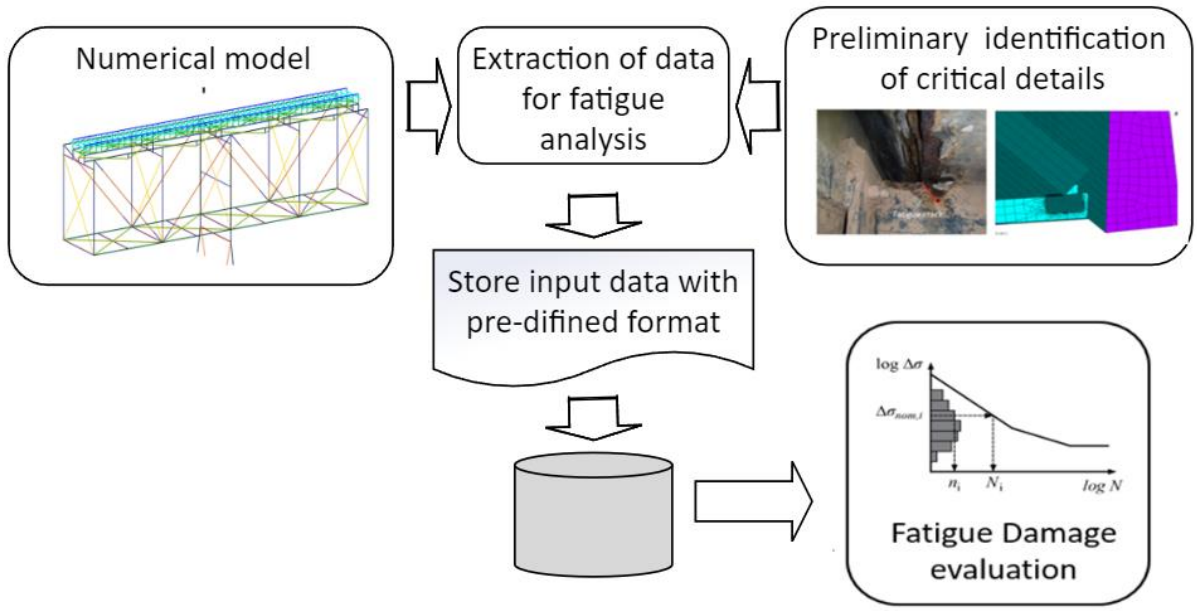

Figure 5: Fatigue damage calculation procedure

3.2.2. Representation of the fatigue state in the virtual model

The graphical representation of the fatigue evolution is based on a color scale, taking into account the level of fatigue consumption (0 to 1). Figure 6 below shows an example of information representation (graphical and non-graphical visualization).

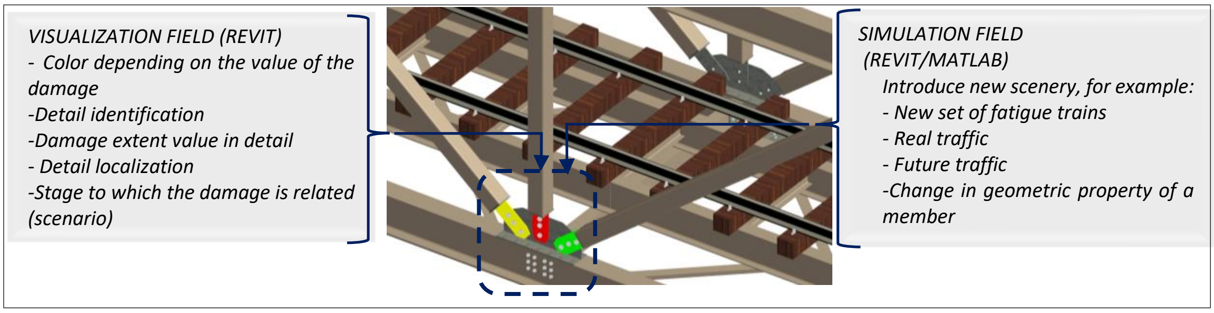

Figure 6: Graphical representation of the fatigue state in the virtual model and simulation

For higher consumption levels (d≥0.95) the color is assigned red, for 0.85≤d<0.95 the color is orange, 0.75≤d<0.85 the color is yellow and for much less critical levels (0≤d<0.75) the detail is assigned green. As previously stated, the representation includes the graphical part and non-graphical information, and it is dependent on data from the calculation and input modules that is automatically transferred to visualization, as shown in Figure 3 and Figure **4**.

The model under study below refers to an existing five-span metallic railway bridge, located in Aveiro district, Portugal (Figure 7).

Figure 7: General view of the bridge under study

It is a truss metallic bridge with riveted connections. Initial steps of model development are shown in Figure 8.

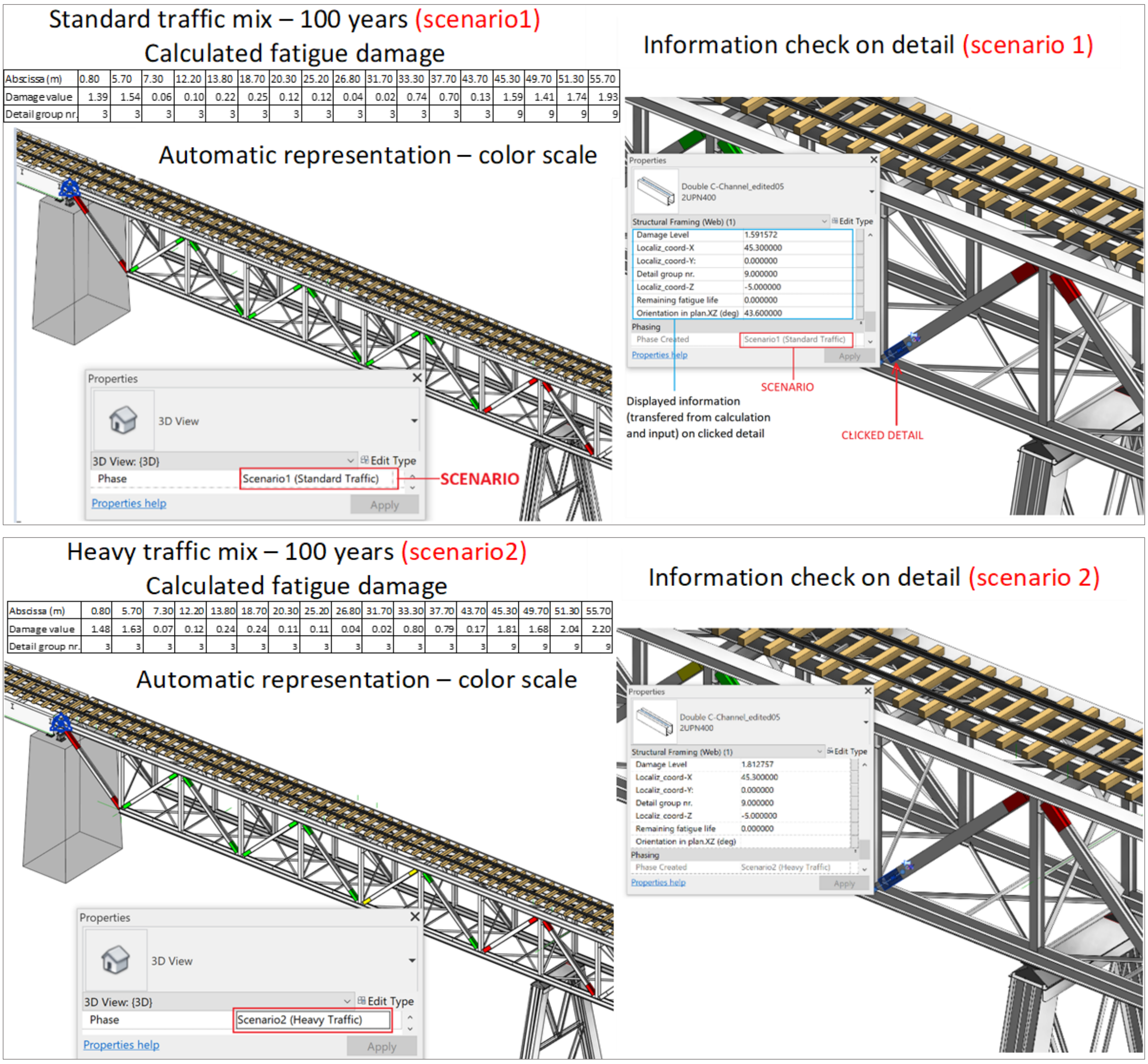

Figure 8: Graphical representation of the fatigue state in the virtual model for the bridge under study-details in diagonals of the 1st span.

The representation of the fatigue state (damage accumulation) in the virtual model (graphical representation and non-graphical information) corresponds to the diagonals of the bridge's first span, simulated for two of the three traffic scenarios specified in Eurocode - EN 1991-2 (CEN 2003), namely, standard traffic mix and heavy traffic mix.

4. Discussion

In this model, where were tested two of the three fatigue train scenarios for a period of 100 years, namely standard traffic mix and heavy traffic mix, the respective representation (graphical part and non-graphical information) is made for details of one of the bridge spans. A real load that is dependent on the measurement of the present traffic load (derived from weigh-in-motion) and that would form one of the scenarios is necessary in order to have a real representation of the fatigue state for the evaluation level proposed in this work, being this part of the next developments. Other scenarios include light traffic mix, future traffic (that can be estimated from present real traffic), and a scenario involving the variation of the bridge's geometric properties. These last two scenarios are very important in the "what if" simulation. The entire process of the proposed simulations have been depicted at framework in Figure 3.

Since the main goal is to identify fatigue-prone details and represent virtually their information (graphical and non-graphical part), the fatigue analysis performed is global (not detailed or local) and correspond to second phase of fatigue assessment in the context of complete fatigue analysis. However, the two scenarios tested here are insufficient, and as previously stated, more scenarios are necessary, with a focus on real traffic.

From a temporal standpoint, the literature refers to real-time, near real-time, and "offline" communication between the physical entity (physical twin) and the virtual part, and so it can be said that this model under development falls into the last two. Since fatigue is a progressive and, in general, non-instantaneous process, real-time communication between the physical entity and the virtual part is of little use; on the other hand, the update of the actual state of fatigue evolution is dependent on the actual accumulated traffic. Similarly, an update related to eventual variation in geometric properties will always be dependent on data from regular inspections and maintenance. Nonetheless, certain internal sub-tasks in the digital model are real-time executable.

At any update, MATLAB and REVIT software must be open, the first for calculation and the second for visualization of the information in the model. When it is just visualization (graphical and non-graphical) of the fatigue state for different scenarios, it can be performed only at software (RIVIT) based on stored information, and also the model can then be exported to other platforms within the interoperability context. The major support of BIM/BrIM consists in the management of information from input to output and modeling process.

5. Conclusions

The methodology and framework for developing a DT model for fatigue assessment is presented and discussed in this study. In order to identify the fatigue prone details and represent the respective information through the integrated process of the proposed model, the fatigue assessment is performed up to phase II from a total of four phases duly described throughout this work. The model consists of three modules, namely, the input module, the calculation module and the output module, all of which are integrated to calculate and simulate various situations, as well as to visualize data (graphical and non-graphical). BIM/BrIM serves as a major support of large-scale data management and modeling. The development of the model follows three steps namely, the elaboration of the information requirements, design of framework and the implementation process. Two of the three scenarios of the fatigue train set are tested on one of the bridge spans. More scenarios are necessary, including the simulation with real traffic in order to have the real state of fatigue. These small tests show promise for subsequent developments that will integrate other scenarios, the review and possible improvement of the automation process which will culminate with the closure of the model.

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