Towards a Protocol for Tangible Cultural Heritage Digital Twin

Chapter 6
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Abstract Cultural heritage includes a large variety of historical masonry constructions. The identification of their structural behaviour is challenging due to the complexities of the masonry constructions and the evolution of multiple phases of construction. Advanced tools for geometric surveying and structural analysis can facilitate the preservation of the cultural heritage but transferring data between these tools remains an issue. In this chapter, we propose a critical discussion on the integration between informative models and digital twins by underling open issues e future perspectives.

Keywords Digital twin · H-BIM open issues · cultural heritage modelling · structural health monitoring · historical masonry structures

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6.1 Introduction

Historic buildings are the result of intricate craftsmanship and varied practices, evolving through architectural alterations, multiple phases of construction, and the natural wear of materials over time. These transformations are often difficult to measure, and the behaviour of masonry presents significant complexity. Consequently, modern numerical models often struggle to capture the nuanced behaviour of these structures, especially those with layered historical developments. Despite this, large-scale numerical models of prominent historical buildings continue to be widely used. However, these models frequently yield results that do not accurately reflect the actual structural dynamics of these monuments. In many instances, calculation methods are applied directly to a detailed 3D representation of the building—often derived from highly accurate surveys—without a prior critical evaluation. It is widely recognized that increasingly accurate methodologies and automated tools are now available in the fields of geometric surveying and structural analysis, serving as essential instruments for understanding and preserving cultural heritage. Both these tools and technologies are integral to the overarching process of knowledge that underpins any conservation project for cultural heritage. However, despite the high levels of accuracy and automation achieved by both technologies and software, transferring data between them remains a challenge, and determining the most reliable methods for translating and exchanging information without data loss continues to be an unresolved issue. The research, in both cases, focuses on improving the accuracy of these important tools to create virtual replicas, the Digital Twins (DT), that closely resemble historic buildings and can simulate their actual structural behaviour with quantitative precision and detail.

Surprisingly, what is often needed is the reverse process.

The real challenge lies in understanding how to reduce the level of accuracy and the amount of information gathered about cultural heritage to enable more reliable analysis and a better, almost qualitative, understanding of its actual behaviour. In fact, while it's evident that precise instruments and methods, which provide increasingly detailed geometric data on historic buildings and allow for complex structural calculations, are essential for enhancing the restoration design process, the growing volume of data requires a careful and critical simplification. This simplification should be informed by other disciplines, such as history, structural intuition, and a blend of empirical knowledge, to develop reliable conceptual models of the buildings, starting from their virtual representations. However, the specificities of historical heritage present challenges in terms of surveying and modeling, primarily due to the need to strike a balance between geometric accuracy, resource input (time and cost), and the manageability of outcomes (file size). Indeed, "research on the so-called 'Historic BIM' should avoid being confined to merely representing historic architecture. Instead, it should leverage the capabilities of electronically interoperable tools to streamline conservation phases" (Della Torre, 2020).

6.2 State of Art in H-BIM and DT: Some Open Issues

Considering the unique nature of historical heritage, it is not feasible to develop a one-size-fits-all system applicable to every case study. However, establishing certain guidelines could assist in structuring operational and conservation-focused information models. To effectively achieve this, it is crucial to address the ongoing challenge of data management, which involves identifying the most suitable procedures for critically selecting, organizing, and archiving information to ensure it becomes an easily accessible resource for the preservation process.

Recent research on the relationship between geomatics and restoration has focused on the continual advancement of surveying and modelling technologies (Brumana et al., 2018; Banfi et al., 2017; Castagnetti et al., 2017; Tommasi et al., 2016; Bonazza and Sardella, 2023). However, to further enhance the effectiveness of the H-BIM methodology as a tool to support conservation activities, it is important to also focus on the information framework that complements the 3D model (Bruno & Roncella, 2019). Specifically, identifying the most valuable data for conservation purposes and determining how best to organize it to facilitate inspection and maintenance planning would be particularly useful. There are many challenging issues that must be addressed in defining a model, starting from information systems (BIM), which, when applied to historic buildings, must contend with an underlying irregularity that stems from semantic issues.

Semantic Issues The international standard IFC (Industry Foundation Classes), recognized as ISO 16739-1, is an open format for data exchange designed to facilitate interoperability between different software systems, such as BIM and structural analysis tools. However, these standards, which are primarily intended for new construction projects, currently lack specific classifications for elements typical of historic buildings (e.g., arches, vaults, and wooden trusses), making a comprehensive definition of all construction elements in built heritage unattainable (Adami et al., 2023; Spanò et al., 2023; Quattrini et al., 2023; Previtali et al., 2020). Additionally, assigning semantic meaning to objects that represent the conservation status of building elements, such as surface decay or structural cracks, remains a challenge. Therefore, one unresolved issue in this field (maybe the main one) is the development of a common vocabulary that, through the creation of specific ontologies, could provide a conceptual framework not only for physical elements but also for the properties, relationships, and actions involved in the conservation process (Acierno et al., 2017). The CIDOC-CRM ontology is a key example, but it requires further development to meet these needs.

Geometric Accuracy or Level of Detail

Unexpectedly, geometric accuracy in a model does not always guarantee the most reliable interpretation of reality, especially in the context of historic buildings. Unlike modern structures, historic buildings are irregular, making parametric modelling difficult and computationally expensive. Reproducing these irregularities with high metric accuracy can be time-consuming, and often, metric precision must be deprioritized to better support conservation activities. Some studies (Ottoni et al., 2017; Bruno, 2017; Brumana et al., 2019; Monchetti et al., 2023) emphasize that the level of detail should be determined by the intended purpose, and geometric precision should align with specific goals rather than always aiming for the highest accuracy. A conceptual model is often more effective for providing access to the necessary information for preservation efforts. The inherent irregularity of historic buildings often necessitates a Mixed Modelling (MM) approach, which combines 3D modelling software for precise geometric reconstruction with BIM authoring software for enhanced information management. The level of geometric detail and accuracy in a model should align with its specific purpose. Federated models, which consist of a geometrically simplified version and a more schematic repository of non-geometric data, are particularly effective for historic structures: the first model captures the full complexity of geometry derived from point clouds, while the second model focuses on detailed information linked to specific geometric elements. Incorporating false colour maps can enhance modelling by representing geometric accuracy. Therefore, although digital surrogates are metrically accurate, they may not adequately interpret the building, unlike simplified interpretative models that provide meaningful insights based on the creator's process. These models serve, instead, as spatially referenced data archives, connecting documents to specific building elements and enhancing the understanding of the building's history. However, a challenge remains regarding the appropriate level of metric accuracy and geometric detail needed for interoperability with structural analysis models. Excessive detail complicates model management and can lead to errors during import, necessitating manual corrections (Barazzetti et al., 2015). In some cases, full morphological complexity is maintained for export, while in others, simplification is required for compatibility with structural analysis software (Oreni et al., 2014; Brumana et al., 2017). It's fundamental to stress that geometric simplification goes beyond merely accelerating the modelling process and reducing complexity; it requires a critical interpretation of the building to justify specific simplifications that enhance the representation of the structure. This challenging process is essential for transforming vast amounts of data into a model that accurately reflects the original information. By incorporating insights gained from understanding the building, critical simplification enriches the model and facilitates the complex task of structural analysis.

Materials and Mechanical Characteristics

BIM entities can have materials assigned through specialized tools in commercial software. While predefined materials are common, they often do not suit historical buildings, prompting users to create new materials (Oreni et al., 2013) or include material information as textual data in custom properties (Celli & Ottoni, 2023; Monchetti et al., 2023). This information can be organized within a specific ontology, allowing details like masonry texture to replace the need to model each individual stone or brick unit (Brumana et al., 2018). Additionally, managing stratigraphy poses a challenge; users can define various layers of construction elements when using a parametric object-oriented modeling strategy (Banfi et al., 2022), facilitating the integration of thermal properties for research on building energy performance (Trani et al., 2021; Thravalou et al., 2023). Mechanical properties of structural elements can be included as attributes in BIM software, with predefined parameters for entities like walls and slabs. Custom properties enable the inclusion of essential mechanical characteristics for structural assessment (Croce et al., 2022). In Archicad, certain values are calculated using mathematical expressions (Moyano et al., 2022; Bruno & Fatiguso, 2018). For wooden structures, properties can be assigned based on visual inspections per the Italian UNI 11119:2004 standard, identifying defects in timber (Celli & Ottoni, 2023; Santos et al., 2022). Research is focused on incorporating properties for the Masonry Quality Index (MQI), which links masonry construction characteristics to structural properties. This classification uses Visual Programming Language for automatic calculation of MQI categories, assigning specific colors to masonry elements based on their category (Calvano et al., 2022). It is important to emphasize that both the geometry and mechanical properties of materials can be defined using the IFC property scheme and later exported. However, a limitation arises because FEM software (such as Abaqus or Ansys) does not support the open IFC format, resulting in the import of only geometry while losing the informational components of the BIM during data exchange. To mitigate information loss, potential improvements include using precompiled tables to translate BIM model properties into formats compatible with the structural model.

Damage: Cracks and Deformation In BIM environment, methodologies for crack mapping are tailored to the model's objectives. One method involves modelling cracks as Superimposed Customized Objects (SOs), with studies generally favouring geometrically accurate representations of damage (De Falco et al., 2024; Chiabrando et al., 2017). In some cases, a simplified model is preferred, supplemented by a detailed information framework. Cracks can also be created in 3D modelling software like Rhinoceros and then imported into BIM authoring software with custom classifications (Spanò et al., 2023). However, correlating cracks with their underlying structures, such as walls or vaults, presents challenges. Edificius software offers an interesting solution by automatically linking crack objects to symbolic representations in plan view, including properties like crack type, width, and potential causes, which align closely with structural restoration needs (Lanzara et al., 2021). Another approach simplifies crack representation using markers attached to walls, providing properties for damage interpretation and risk assessment for intervention planning (Barontini et al., 2022; Mora et al., 2021). Subtracting a Solid (SS) from the affected structural element is a more time-consuming method that allows for variable crack widths (Castellazzi et al., 2023). Additionally, correlating cracks with established collapse mechanisms through associated data sheets is a potential avenue for development (Quattrini et al., 2017). Structural damage is not limited to cracks; deformations are often identified through instrumental surveys. Detailed 2D drawings represent these deformations, sometimes using symbolic notations for clarity (such as out-of-plumb walls, deflections in beams, vaults, or pavings) (Barontini et al., 2022). The modeling of structural deformations in BIM is a topic of debate; while some research aims for high metric accuracy by replicating irregularities in historic buildings, others prefer idealized representations to enhance interoperability and manageability of the information model. In rectified modelling, precise assessments of deformations are made by comparing the ideal BIM model to point cloud data. This distinction emphasizes the roles of point clouds, which accurately reflect reality, and HBIM models, which, although simplified in geometry, contain valuable information for interpreting ongoing phenomena. For example, interpretative modelling allows for differentiation (and provides various representations) between deformations that occurred during the construction phase—which are not necessarily indicative of ongoing failure—and those closely linked to stability issues within the building, thus holding greater significance for planned conservation (Lo Turco et al., 2017). In simplified models, properties like beam deflections or out-of-plumb walls are recorded within rectified geometry, enabling thematic queries and the inclusion of detailed 2D drawings. Interoperability between BIM and finite element models is currently limited by IT and semantic challenges within software and exchange formats.

Diagnostics As far as investigation results, they are more readily accessible when they are spatially referenced within HBIM models and directly linked to the building element on which the test was conducted. Two main approaches can be identified: test results can either be incorporated as properties of the elements—which prevents precise localization since the results apply to the entire object—or represented through superimposed objects that symbolically correspond to the diagnostic investigation. However, the latter option complicates the semantic connection between the investigation and the construction element. In this second scenario, these objects can be linked to a set of customized properties, including test type, execution date, instrumentation used, summarized quantitative results, brief interpretations, and links to images and reports. The choice of the most appropriate method depends on the objective of the model, but above all on the type of test: some tests require precise localization (such as endoscopies, flat jacks, penetrometric tests, hygrometric ones, some sonic tests, etc.); others involve larger surfaces (thermography, investigations with radar or metal detectors, etc.). Additionally, the outputs differ significantly: quantitative data can easily be integrated into the properties of the objects and correlated with other information, such as mechanical characteristics; conversely, raster images (like thermography) need accompanying qualitative annotations for proper interpretation. A mixed approach is feasible (Mandelli et al., 2017): utilizing a developed platform, the representation method varies based on the test type: specific information is incorporated alongside symbolic objects, while investigations covering larger areas are mapped as an additional layer on the surface. Furthermore, thermography images and Ground Penetrating Radar (GPR) results for extensive surfaces can be directly projected onto wall objects (86), forming a new custom material (CM) whose properties align with the descriptive data of the test. This visualization facilitates immediate correlation between thermographic investigations and surface degradation within the three-dimensional model.

Lastly, the ontology developed in previous studies (Fiorani & Acierno, 2017) enables the conceptualization of diagnostic activities by defining the "Investigation Process" domain. Customized entities and properties are established to relate the tests to the architectural surfaces being investigated, emphasizing conservation efforts.

Some Notes: From HBIM to DT In simple terms, there appear to be two main approaches to translating reality into reliable models. The first approach involves refining the outcomes of even the most sophisticated numerical analyses by observing the actual behaviour of structures over time through both static and, more importantly, dynamic monitoring. This method is reminiscent of the techniques employed by ancient master builders, whose primary tools were experience and direct observation of past damage and collapse mechanisms. When opting to retain all available information for precise 3D numerical models, the geometry must be adjusted, and irregularities reconstructed to ensure reliable analysis results, especially regarding stress. The second approach emphasizes simplifying the redundant information from a highly accurate 3D model from the outset, enabling better control over the final analysis results. However, the simplification process itself is complex; it requires a clear understanding of the most likely collapse mechanisms, which can vary between different structures and often follow a typology-based approach. Furthermore, it demands the ability to predict expected outcomes, at least qualitatively. This level of understanding is only achievable through deep empirical knowledge, which remains the most fundamental and effective means of understanding and preserving cultural heritage.

6.3 Digital Twins, Prediction Capabilities, and Structural Health Assessment of Cultural Heritage

The use of DT in structural engineering has become increasingly widespread in recent years, providing a comprehensive framework to emulate and understand the behaviour of complex systems, including historical and monumental buildings. A key factor in any model, whether physical or mathematical, is its ability to accurately describe the essential features of the system it represents. This requires a methodical approach, involving multiple phases of model development, beginning with the analysis of available data, followed by synthesis to filter out unnecessary information, and culminating in the creation of the model. Physical models, while not suitable for representing structural systems when the scale becomes too small, are highly effective in simulating extremely complex behaviours, especially when replicated on a scale as close to the original as possible. In contrast, numerical models, such as Finite Element (FE) models, are well-suited for solving problems where theory aligns well with real-world observation, as in the case of linear elasticity, within the limits of instrumental or computational approximations. The relevance of physical models becomes particularly evident when they corroborate numerical models with experimental data. Numerical models, therefore, play a crucial role in supporting these tests, incorporating data gathered from archival research and geometric surveys. Regarding experimental data, they play a fundamental role in enriching the model, enabling the virtual representation to mirror real-world conditions more accurately. Among the techniques for collecting experimental data, vibration-based methods are especially important, as they allow the dynamic characterization of structures. Such measurements provide valuable insights into the global behaviour (Ceravolo et al., 2016; Ierimonti et al., 2023; Monchetti et al., 2024a, 2024b) of a structure at reduced costs and with minimal invasiveness (ICOMOS, 2003), a critical factor for historical structures, where preserving material integrity is essential (Ceravolo et al., 2019; Lorenzoni et al., 2016). Furthermore, as both the structural system and the surrounding environment are constantly evolving, models must be designed with the ability to update and incorporate new information from monitoring systems. Continuous or periodic monitoring can detect changes in system properties, such as those caused by environmental factors like temperature fluctuations and differentiate between physiological (normal) and pathological (abnormal) changes in behavior (Deraemaeker et al., 2008; Ubertini et al., 2017; Zini et al., 2024; Marafini et al., 2023). When such pathological behaviors occur, they should be reflected in the models by updating the constitutive laws of materials, or even geometric and topological properties. Through the process of Model Updating (MU) (Mottershead & Friswell, 1993; Ierimonti et al., 2023; Pepi et al., 2020; Monchetti et al., 2024a, 2024b), the predictive capabilities of these numerical models can be enhanced, particularly by aligning them with the experimental results obtained from vibration measurements. The goal is to develop a continuously updated model with predictive capabilities. However, simply updating a model does not automatically grant predictive abilities. These capabilities must be demonstrated through physical interpretations and experiments, at which point the updated model can be considered verified. A predictive numerical model can then be employed for high-level Structural Health Monitoring (SHM), including prognosis and estimation of the residual life of a structure. Within a civil SHM framework, this twinning perspective can be enabled by the assimilation of data through data-driven structural health diagnostics, possibly accommodating the quantification and propagation of relevant uncertainties, such as measurement noise, modelling assumptions, and environmental and operational variabilities. The resulting updated digital state should then allow for the prediction of the physical system evolution.

Considering the above, the concept of DT in structural engineering should embody a model that is simultaneously probabilistic, so accounting for the inherent uncertainties that define the nature of structural systems, capable of rapid updates to track real-world changes in real time or even anticipate them, and, lastly, should be a multiphysics model characterized by extremely high fidelity. Developing a digital model with the ability to precisely capture real-world variations requires the collection of a wide range of data types. Their integration and fusion enable a comprehensive view of the environment in which the structure is situated. In fact, it is crucial to recognize that each structure is embedded in a surrounding system, directly influenced by environmental conditions such as temperature, humidity, and precipitation, and indirectly by changes in the soil, which can alter its overall behaviour. The overall aim is to integrate data from various sources, including experimental and environmental monitoring, to create an evolving model that not only reflects current conditions but also predicts future behaviours (Fig. 6.1). The continuous updating of these models based on real-time data is what gives DT their advanced predictive capabilities. Among the data that can be used to enrich the model to make it a predictive DT, there are the data that directly characterize the structure (frequencies, cracks, temperature, displacement, rotations) (Ceravolo et al., 2017) and then the ground on which it stands (humidity, water table height) and the surrounding environment (temperature, rain, etc.) (Ceravolo et al., 2021). This data can be acquired on-site via on-site sensors or via remote technologies. The latter include data acquired through satellite remote sensing, which enables the collection of information on various structures or regions without the need for installing monitoring systems on-site, an approach particularly beneficial for historic buildings. Satellite data are highly beneficial for measuring displacements (Coccimiglio et al., 2024) and other parameters, such as soil moisture or temperature (Coccimiglio et al., 2022), particularly in situations where ground measurements are unavailable. They facilitate cost savings and, in some cases, reduce time requirements, as this data is often readily accessible.

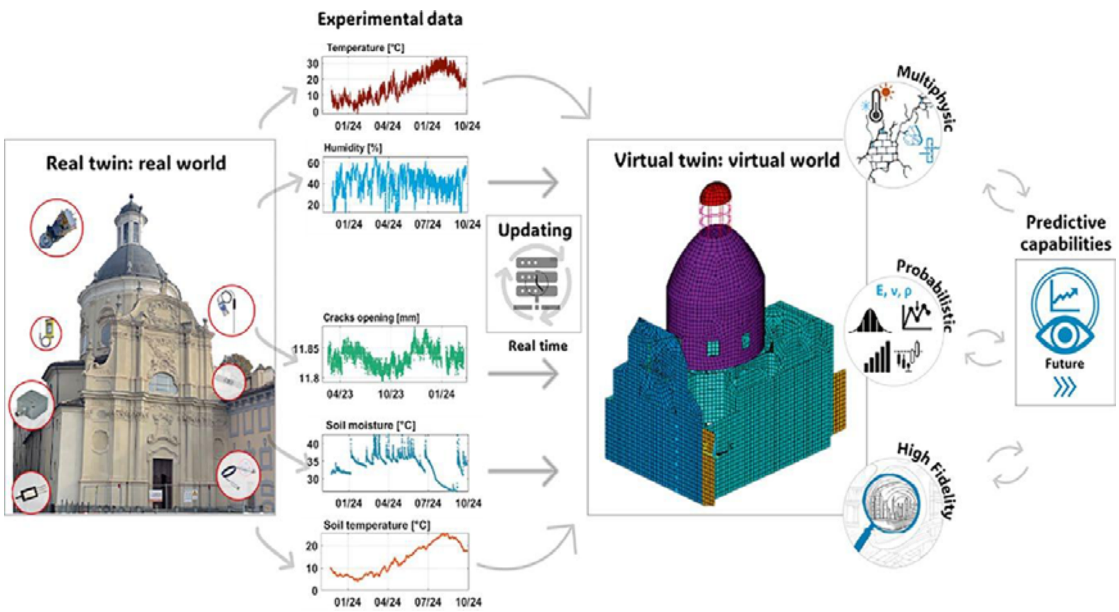

Fig. 6.1 The concept of digital twinning in structural engineering: the process towards predictive capabilities

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