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Article

Digital Twin: Research Framework to Support Preventive Conservation Policies

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Abstract: Preventive strategies for the conservation of heritage sites have gradually been preferred to curative approaches because of their ability to maintain their significance. Furthermore, most experts now agree that conservation management of heritage places based on a common understanding of their cultural values is essential to address all the particularities of their contexts. Recently, significant research has demonstrated the potential of Heritage Building Information Modelling (HBIM) for the collaborative data management in conjunction with conservation projects. The recent development of HBIM web platforms illustrates the value of strengthening the link between the digital model and the physical realm of heritage assets. This paper advocates the application of Digital Twin's (DT) principles, using HBIM models as a digital replica, to support the preventive conservation of heritage places. Based on an extensive literature review, a comprehensive framework that integrates the DT into the management plan process for the preventive conservation of built heritage is proposed. Several recommendations for its implementation are finally discussed, such as the identification of tangible features of significance, the threats associated with their integrity and the corresponding mitigation strategies, with particular emphasis on the value assessment process. The result is a data model for structuring information on preventive conservation strategies. This framework provides the basis for future implementation and demonstrates the need for a DT approach in this context.

Keywords: HBIM; Digital Twin; Preventive Conservation; Heritage documentation; risk management

1. Introduction

Since the publication of the Venice Charter [1], the notion of Cultural Heritage has been broadened to include a wider range of forms and scales [2] as illustrated, for example, by the recommendation on the protection of moveable cultural property [3] and the convention for the safeguarding of the intangible heritage [4]. The growing scope of Cultural Heritage [5] has led international institutions and organisations in the field to review the principles guiding its conservation and to develop new recommendations accordingly [2]. In fact, as shown by the establishment of the PRECOM³OS chair in 2009 [6,7], awareness has been progressively raised among professionals and experts in the field about the need to shift from a curative towards a more preventive approach to better retain the cultural significance of Heritage assets [7,8]. As argued by Van Balen [9], the application of preventive conservation principles, essentially based on regular monitoring and maintenance work, allows better preservation of the immovable heritage and a reduction of the costs linked to conservation activities. As an example, a blocked gutter can indirectly cause water infiltrations, resulting in irreparable damage to significant interior features, such as wall paintings.

Necessary restoration work never allows the full recovery of the affected elements, and always imply major expenses. Rather, the preventive approach suggests intervening upstream by early detection and understanding the deterioration process through regular monitoring of the site. The need for interventions and the associated costs are then reduced (in this case, the removal of the leaves in the gutter preventing water drainage) and the potential effects of the agents of deterioration are prevented or significantly limited.

As the notion of Cultural Heritage has broadened, the evolution of the understanding of its meaning has also gradually influenced the evolution of heritage conservation practice [2]. Understanding and defining the cultural significance of heritage places, as one of the major challenges facing specialists in the field of Heritage Conservation [5], is essential to the design of preventive conservation strategies [10]. Although value-based approaches have been progressively adopted both in academic and professional spheres[11], none of the typologies of values proposed since 1979 and the publication of the Burra Charter [12] has been universally adopted [11]. Fredheim and Khalaf argue that previous value typologies have failed mainly because they were not inclusive enough and because of the lack of an additional review mechanism. First considered from a more essentialist perspective, where values are considered to be intrinsic to material elements [13], cultural values are now seen as multiple and mutable [2]. The assessment of the significance of an asset is no longer considered as a punctual event but rather as a social process of heritage creation [5]. Given the conflicting aspect of values, it is crucial that statements of significance include all interpretations and meanings of heritage places in order to provide stakeholders with the necessary resources to negotiate their conservation balancing the different interests involved [10].

The challenges faced by heritage documentation specialists due to the increased variety and complexity of information sources [9] are reinforced by the radical changes of heritage conservation practice [2] observed over the last century. Before developing preventive conservation strategies, a good understanding of the heritage site and its context, including the assessment of its multiple values, is necessary [10]. In this regard, the complex management of information related to the documentation of heritage places involves critical reflection on the adoption of an appropriate Heritage Information system (HIS). The need for 3D visualization in Geographic Information System (GIS) to enable better visualization and analysis of complex issues related to elements of significance [7] has led researchers in the field to progressively consider HBIM as a relevant alternative [14–16]. Although most of the research work related to HBIM initially focussed on the difficult three-dimensional reconstruction of geometrically complex built heritage elements [17,18], growing attention is being paid to linking the semantic of Heritage places to their HBIM models [19] and to the development of HBIM web platform [20].

In view of previous concerns, the capacity of HBIM to support stakeholders in implementing preventive conservation activities based on the recognition of its multi-layered significance should be investigated [14]. The integration of these dimensions in HBIM process appears to be crucial as it addresses two major issues in the field of the heritage documentation. On the one hand, it limits the risks of data obsolescence by integrating all related data into the model for use in conjunction with the operation and maintenance phase of the life cycle of the properties, thus avoiding these data being stored in local databases [21]. On the other hand, it has been argued that the limited interactions among the different spheres of heritage conservation often results in a problematic disconnection between the initial phases of a project, such as the preliminary studies, and the actual interventions in the execution and maintenance phases [5]. Semantically enriched HBIM has demonstrated its ability to dialogue with a wider range of stakeholders through multiple visualization and representation tools [22]. In this regard, such models could ensure more efficient transmission of information among the stakeholders along with all the phases of historic places' lifecycle. In addition, the recent development of HBIM web interfaces illustrates the need for further research to strengthen the relationship between the digital model and the real world in order to better support the preventive conservation of historic places. The application of "Digital Twin" principles to support such an approach has been suggested in a previous work [14].

In this research, we focus on a comprehensive method to support site managers in the preventive conservation of their assets by providing them with tailored information about the impact of their decisions on the preservation of features of significance. This method first implies the integration of cultural values as interpretable data into the HBIM and the subsequent use of models as a digital replica in a Digital Twin environment to monitor the change, detect risks, suggests possible solutions and assess the potential impact of both threats and interventions on significant elements carrying heritage values. The rest of the paper is structured as follows. First, a section devoted to the state-of-the-art aims to describe the current state of research in the field. A detailed description of the method developed is presented in the third section. The fourth section discusses the results of this work and provides a set of rules towards the implementation of the method.

2. State of the Art

2.1. Preventive Conservation Management

The evolving scope of Cultural Heritage has led experts in the field to question their approach towards the preservation of heritage places. Increasingly, the common belief that decisions related to the conservation of heritage assets should be based on a clear understanding of their cultural significance is reflected in international guidelines. Initially mainly oriented towards the safeguarding of the material substance of the built heritage, the main goal of conservation was redefined in the Burra Charter as to "retain their (its) cultural significance" [23]. Considering the latter, the definition of meanings and values associated by society to the immovable heritage is an essential step towards their conservation. Although the necessity of basing decisions related to the conservation of heritage places on their significance is not a new concern, the notion of heritage values has considerably expanded according to the new challenges faced by society and to the increasing scope of Cultural Heritage. According to Avrami et al. [5], heritage creation must be understood as a socially constructed process specific to a spatial-temporal complex. The significance of these places lies in all the meanings and interpretations attributed to their tangible and intangible features by society and decisions made for their conservation are the results of negotiation among the stakeholders involved leading to the prioritization of certain values over others.

2.1.1. Preventive Conservation and Risk Management

In recent decades, increasing attention has been given to the control phase of the conservation cycle to monitor the evolving condition of the site and its context and, equally importantly, to evaluate the effectiveness of previous conservation actions. In fact, preventive conservation has gradually been considered as the most appropriate approach to retain the significance of a place. Throughout the 20th century, the growing consideration for maintenance in the international doctrine [1,12,24] illustrates the progressive paradigm shift which led experts in the field of heritage conservation to switch from a curative towards a more preventive approach [7,8]. The 1999 review of the Burra Charter even defines maintenance as being "fundamental to conservation" [25]. Preventive conservation refers to a strategic approach towards more sustainable preservation of the built heritage taking advantage on systematic maintenance and regular monitoring of tangible assets to "*slow down the process of decay*" and better retain the cultural significance associated with them by society. In the framework of preventive conservation, the strategic planning of maintenance activities must be based on a deep understanding of the buildings concerned through a multidisciplinary and holistic approach defined by Watt as *"building pathology"* [26]. This multidisciplinary process studies the "*effects (damages), the cause and the remedies*" [27] of unexpected failures *"in the design, construction and use of the buildings"* [26], as opposed to natural aging process and decay. More specifically, building pathology intends to reveal the underlying mechanism causing the identified degradation processes to tackle the very cause of defects rather than their consequences.

By slowing down the decay of building elements, building pathology aims at extending building elements lifecycle while ensuring their statutory compliance (meeting requirements of current regulations) and functional suitability (meeting functional, performance and users' expectations). Beyond the analysis and diagnosis of existing faults, building pathology also requires the prognosis of potential defects and threats. *"Preventive conservation …, is based not only on assessment of state, but also on periodic assessments of risks and threats. By addressing deterioration causes and facilitating early damage detection, intervention is kept to a minimum"* [7]. As highlighted by Heras Barros, dealing with the risks faced by heritage sites is another significant aspect of preventive conservation. Considering the growing threats faced by cultural heritage places in a context characterized by constant globalization and fast climate change, Stovel highlighted the need for advance planning and development of disaster prevention [28]. The management of disaster risk, defined as the "product of hazard and vulnerability" [29], is crucial to reduce the potential loss of cultural significance. Research regarding risk preparedness in a Cultural Heritage context highlights the necessity of identifying, through an in-depth analysis of the condition of places of significance to understand the change over time and identify the disturbances and present effects of damages due to past agents of deterioration. Apart from defining past and present deterioration processes, the condition assessment must determine potential future threats through an in-depth analysis of the assets and their context by a multidisciplinary team of experts [10]. On this basis, conservation strategies can be elaborated to mitigate the possible effects of the identified threats. In this regard, Heras Barros proposed, in 2014, a *"3D GIS monitoring tool"* to support preventive conservation strategies for the city of Cuenca, Ecuador, including the aspect of risk management. Taking advantage of CityGML data models in GIS environment, this work demonstrates the need to take advantage of reality-based 3D models to support the implementation of monitoring activities. Additionally, Malcolm [27] suggests that Computer-Aided Facilities Management (CAFM) software can benefit from the data contained in BIM models to "*quickly retrieve information*" about expected performances. From this perspective, extra layers of information about "*manufacturers' guidance on repair and replacement methods*", for instance, should be included in the models. When designed to "*capture data about the performance of the building and its services*" such models could provide tailored feed backs particularly useful for the elaboration of future projects.

2.1.2. Conservation Process and Management Plan

Alongside this significant evolution, and together with emerging considerations for the integrity and authenticity of heritage places [30], awareness about the need to elaborate and implement the appropriate management and protection measures to retain the cultural significance of heritage places arose. Since the publication of the Burra Charter, the importance of elaborating values-based management plans has been highlighted. The Burra Charter Process proposed in the significant 1999 review of the document [25] and the 1998 Sheffield Template for a Model Conservation Plan [31], among others, illustrate the growing recognition of the need to develop a planning method for the conservation of cultural heritage [32]. The Planning Process Methodology proposed by Demas [32] clarifies previous models and divides the process into four main steps: Identification and Description, Assessment and Analysis, Response, and finally Periodic Review and Revision. Compared to the process applied in medical care in the ICOMOS principles for the analysis, conservation and structural restoration of architectural heritage [33], the main steps of the preservation cycle are also known as anamnesis/analysis, diagnosis, therapy, and control [7,34]. This process has been adopted by several researchers and conservation experts to support maintenance and monitoring actions in the framework of preventive conservation approaches. For instance, in 2012, the Disaster Risk Management Plan process proposed for the case study of Petra [10] illustrated the importance of risk preparedness for the management and maintenance of heritage places. The proposed method leads to the identification of the risks and their potential impact on the cultural significance of heritage sites, the development of strategies to mitigate the effects of these threats and their evaluation through cost–benefits analysis considering the level of uncertainty and the magnitude of the risk.

Including this extra layer in the identification of all endogenous and exogenous factors and issues (potentially) impacting the preservation of the tangible elements of heritage places, third step in the Burra Charter process [23], appears particularly relevant in the case of preventive conservation.

2.1.3. Cultural Significance of Heritage Places

Because the conservation process, particularly the value assessment, has come to include a wider range of stakeholders, it is now critical to allow experts to better communicate with a broader audience about the myriad meanings of the built heritage and to enable them to explicitly justify their decisions related to the conservation of features of significance [11]. In this sense, value typologies have for a long time been used as an instrument allowing the interplay among the different stakeholders to define the different values of an asset and negotiate their relative importance. The Nara grid proposed in 2008 by Van Balen [35] is an example of value typologies, based on the different aspects and dimensions of heritage suggested in the 1994 Nara document on Authenticity [36]. More recently, Fredheim and Khalaf highlighted that "*The sense that a comprehensive, universally applicable value typology is an impossibility is increasingly evident in the literature*" and suggest, among other reasons, that these typologies fail at capturing "*the full range of ways in which heritage is valued*", essentially because they are not inclusive enough and because they lack a mechanism for reviewing and integrating past assessments of significance [11]. Rather than a new value typology, they propose a more holistic and inclusive framework for assessing the significance of heritage assets, deconstructing the process into the three main phases depicted below.

Based on Stephenson's Cultural Values Model [37], the first stage concerns the identification of valuable elements and their classification into three categories: forms, relationships and practices. Although the last ones refer to intangible aspects, being the interplay between the human and the heritage site (including spirituality, memories, stories, sense of the place, etc.) and the processes and events related to the site (historical events and processes, human systems and activities, natural processes, etc.), respectively, the forms category concerns all tangible naturally and culturally valuable elements. The process needs to be repeated at all appropriate scales until all the significant valuable features have been identified. Indeed, heritage objects are considered to form part of a heritage site (for example a building on a site), but the heritage object can also be considered as a heritage site containing other heritage objects (for instance a staircase in the building). The goal of this phase is to provide a very clear description of all elements bearing heritage values, avoiding as much subjectivity as possible. The clear distinction of the tangible elements allowing the perception of all the values associated with heritage assets is the most striking advantage of part of the process. Another strength is that it captures both observable/surface values (referring to the observation of present features of significance) and embedded values (past surface values that became intrinsic over time), allowing "past interpretations of significance (to play) a role in the present". In a second phase, after having defined the valuable features of the asset, four aspects of value (associative, sensory, evidentiary, and functional) allow to explain why each heritage object is valuable. The explicit description of the reasons for the significance of the different features, if short and using accessible language, is a powerful tool to include non-expert stakeholders and inform them during the conservation process. Finally, conserving heritage implies negotiating the myriad interpretations and value judgement and inevitably leads to favouring some over others. Then, defining the relative importance of all these layers of interpretation appears to be crucial. The third stage of Fredheim and Khalaf's framework suggests the use of "qualifiers of value" (authenticity, rarity, condition) to help to specify how valuable the identified features are. This third phase in their method for the elaboration of a statement of significance is essential because it makes the links between the interpretations, judgments, values on the one hand, and how perceivable they are through the observation of the physical object on the other hand.

2.1.4. Heritage Information System

Heritage information, according to Letellier [38], encompasses "*the activity and products of recording, documenting, and managing the information of cultural heritage places*" that should be regarded as an ongoing process supporting stakeholders in making decisions along with the different phases of the conservation process. Santana further specifies that "*Heritage information should provide relevant and timely data in order to proceed and evaluate the role and action of each of the work phases*" [39] of the conservation cycle model proposed in 2000 by Demas [32]. More specifically, when dealing with the management of heritage assets with a preventive conservation approach, ensuring access to accurate and reliable information about the site's condition is essential since it provides stakeholders with the necessary references to monitor the change [38]. Specific aspects of data related to the immovable heritage challenge its management such as the temporal dimension of such information, its heterogeneity and complexity, the multiplicity of stakeholders targeted, the value of the data collected compared with the difficulty of recording [7,40] and so on. Moreover, the technological improvements accomplished during the last decades resulted in an increased variety and complexity of information sources [9]. Finally, Billen et al. [40] argued that the product of heritage information, once collected, is hardly often stored in databases and organized according to standards.

Considering the latter, adopting the appropriate HIS for the digital management of such data is critical not only to support the implementation of the preventive conservation management of heritage places, but also to ensure the transmission and accessibility of the generated knowledge to further stakeholders and generations. Such systems, taking into account the variety and diversity of assets forming part of our Cultural Heritage [41], should be designed based on a clear understanding of heritages sites, their context, and the conservation goals defined. According to Heras Barros, the information collected should be concise, relevant, easily understandable, and interoperable [7]. Considering the above-mentioned complexity, it is not surprising to observe that commercial solutions available on the market can hardly address all the needs of the stakeholders involved [40]. In the field of heritage documentation, the last decade has been characterized by a constantly increasing focus on reality-based 3D modelling [19], mainly made possible by the technological improvements of Data acquisition technologies (Terrestrial Laser Scanning (TLS), Aerial and Terrestrial Photogrammetry, Electronic Distance Measurement (EDM), etc.). This phenomenon can be illustrated by the significant amount of research focussing on the development of the third dimension in Geographic Information System (GIS) and Computer-Aided Design (CAD) environments. At the same time, researchers in the field of Cultural Heritage have progressively considered Building Information Model/Modelling/Management (BIM) and its interoperable exchange format (Industry Foundation Classes (IFC)) as a relevant alternative for the management of information [14] related to immovable heritage. Rather than being in conflict, BIM and GIS can be considered to be complementary [42], because they deal with different issues and scales, and even though no existing commercial software has yet proposed a fully integrated BIM-GIS solution, the current state of the research seems to indicate the progressive merging of both. Hybrid systems taking advantage of geospatial data management in GIS and reality-based 3D modelling tools and technologies have already been explored and proposed [7,43].

Considering the numerous benefits of BIM applied in heritage/historic context, in terms of data modelling and management, the potential of HBIM data models to support preservation strategies should not be neglected. In light of previous considerations, integrating HBIM models in the global reflection of heritage assets management is critical to ensure the transmission of collected data to future generations.

2.2. HBIM

As is well known, BIM refers to a collaborative process among the stakeholders of a construction project for the exchange of information through an object-based digital model. BIM originally aimed at improving the construction sector's competitiveness by significantly reducing constructions' costs and time avoiding a great number of errors during the execution of the works. To do so, the simulation of both the actual construction of the project and all the interactions among professionals during the execution of the works are performed. In the last decade, the numerous studies on the application of BIM solutions for 3D parametric modelling of heritage places have demonstrated the potential of HBIM models to support their conservation. Bassier et al. recall that the exchangeability of information between varying parties is paramount in the framework of heritage conservation projects. The characteristic features of BIM modelling solutions that led heritage recorders to gradually consider HBIM models as a relevant alternative for the documentation of historic places are probably the collaborative aspects of BIM's process, the IFC open and interoperable format and the 3D parametric modelling tools [44]. In a review of BIM for Heritage Science, Pocobelli et al. [45] observed that "*built heritage is characterised by complex morphology and non-homogeneous features, which clash with BIM's standardised procedures*". Although most researchers have been committed to addressing the issue of the complex modelling of heritage objects with irregular geometries, previous research on HBIM has also focussed on other aspects, such as: optimizing "Scan-to-BIM" modelling processes to improve the cost-effectiveness of such methods [18,19,46], the use of HBIM models for data dissemination and collaboration among stakeholders through Web applications, Augmented Reality and Virtua Reality technologies [22,47], interoperability between BIM and GIS solutions [43], condition assessment and structural analysis in the BIM environment [44,48], and so on.

A gap is highlighted with respect to "BIM's information holding capacities, namely the storage of cultural and historical documentation, as well as monitored and simulated data relevant for preventive conservation" [45], illustrating another growing concern, which is the difficulty for HBIM models in embodying and representing the different layers of meaning and knowledge associated with the tangible features of heritage places [19]. It has been argued that ontologies have the potential to assist the management of the built heritage by identifying threats and their potential harm to features of significance with the according loss of significance, and subsequently suggesting conservation actions [49]. Recently, Yang et al. proposed briding the gap between geometric modelling in the BIM environment and the semantics knowledge modelled in ontologies [19]. Alternative solutions to address this issue have also been proposed such as the use of BIM Free Open Source Software (FOSS) due to its increased flexibility in the structuring of data, which makes it possible "to adapt the software and DBMS (DataBase Management System) to the Cultural Heritage needs and not the opposite"[50]. This method makes it possible to capture the entire complexity of heritage information with all the interplay and relationships between the different data and enables stakeholders to extract key information by performing complex queries. Additionally, it has been suggested that the Internet of Things appears to be the next important challenge as it spreads within the construction sector [40], and it has been proposed to take advantage of these infrastructures to support preventive conservation of immovable heritage [14,51]. Considering the previous considerations and V. Heras' recommendation to focus future research on "how these technologies (ICT tools in heritage conservation) can improve and support heritage planning and management", the concept of the Digital Twin and its possible applications in the field of Cultural Heritage will be discussed in the next section.

Another issue regarding the implementation of BIM in the heritage sector has been raised, which is the inefficiency of collaborative data management, despite the theoretical gains announced by BIM software developers, mainly due to the insufficient or even non-existent involvement of "*non-technical heritage stakeholders who do not use BIM software*".

The work of these stakeholders is then not synchronized in BIM models leading to a situation in which *"dispersed data is produced, duplicated information is generated and other stakeholders' contributions are sometimes not taken into consideration"* [20]. To address this issue, Palomar et al. proposed an online platform to include all stakeholders involved and synchronise the information contained in the model in real time.

2.3. Digital Twin

Even though the concept has carried different names, the early stages of the DT idea can be found in the first years of the 21st century. Indeed, back in 2002, Michael Grieves presented a project for a Product Lifecycle Management (PLM) centre [52], where all the basic principles of the DT concept were present. In 2014, Grieves defined the Digital Twin as a "virtual representation of what has been produced" and indicates that comparing the Digital Twin "to its engineering design (allows) to better understand what was produced versus what was designed, tightening the loop between design and execution" [53]. Initially mostly applied in astronautics and aerospace area (Grieves and Vickers, 2016), recent progress in IoT (Internet of Things) infrastructures and the development of low-cost and reliable sensors has led specialists in building physics to consider such technologies to support monitoring strategies for the preservation of heritage sites. According to Klein et al. [54], beyond the typical parameters monitored for collection care purposes, mainly focussing on the control of microclimatic conditions (temperature, relative humidity, etc.), other variables such as noise pollution, lighting condition, air quality, air flow, attendance, and people flow, for instance, can be measured and/or monitored. Considering the growing threats faced by heritage places, monitoring physical factors that can potentially threaten the integrity of tangible features of significance can be particularly helpful in supporting preventive conservation strategies [55]. Implementing DT for the management and preservation of CH assets requires adopting a collaborative integrated approach and a strong interplay among heritage recorders, conservation experts [38] and ICT specialists (Information and Communication Technologies). Devices to monitor specific factors influencing internal and external conditions of assets to support preventive conservation approaches have for long been used by specialist in heritage conservation [56]. Based on observation, control, and recording of a wide variety of critical physical parameters, sensors allow experts to detect abnormal changes in environmental conditions that could threaten buildings and sites' integrity. Monitoring several factors and defining trigger values and specific conditions under which the sites' integrity might be endangered, the joint analysis of these parameters can help to identify issues and potential threats related to the initial design, spatial configuration, occupancy, the urban or rural setting, the managing context, among others, and understanding the process behind them in order to suggest further possible solutions. Moreover, as mentioned by Moraitou et al. [57], in addition to the obvious short-term benefits, long-term storage of data provided by the sensors can contribute to a better understanding of interferences between CH assets and their environment by comparing such data to the information collected along with the different phases of conservation projects.

3. A Comprehensive Method

The goal of this article is to propose a data model and a reasoning method that allows integration of semantically enriched HBIM models in the DT environment to support preventive conservation strategies. Several advantages related to the adoption of such a method can be highlighted. First, the risk of obsolescence of HBIM models would be significantly reduced by integrating them in the general management of heritage places, and their use would no longer be limited at the project stage. The latter also implies a better transmission of the knowledge generated about heritage sites to future generations. Then, the automation of analysis processes in DT environment, providing tailored information to decision-makers for the conservation of their assets, will enable site managers to spare resources in the long term. Finally, an important added value of the method proposed is related to the greater awareness of stakeholders on the potential impact of the conservation actions they intend to implement on the cultural significance of heritage sites. Indeed, as has been argued [14], the automated analysis and simulation processes in the DT environment should be aware of the heritage values associated with the tangible elements forming part of such sites. Adopting such an approach requires rethinking and adapting some specific aspects of the four identified steps of a management plan process.

Synthetizing and bridging the gap between previous conceptual models, this chapter proposes a specific process for the preventive conservation management of heritage assets and further highlights key phases towards the implementation of the DT method. The models we refer to are essentially the Demas Planning Process Methodology [32], the conceptual model for disaster risk management proposed in 2012 for the case study of Petra [10], the Burra Charter Process [23], and the preventive conservation approach process proposed by Heras [7]. Actually, the main structure of the planning process proposed here corresponds to the four main steps of the conservation process identified in the 2003 ICOMOS charter [33] (Analysis, Diagnosis, Therapy and Control).

3.1. Analysis

The main objective of the first phase is to provide the stakeholders involved with a clear understanding of the site, its context as well as with a good definition of the management plan's scope (Figure 1). Prior to the analysis, the site should be clearly identified and briefly described, the stakeholders to involve in the different phases of the process and their corresponding objectives and expectations regarding the management plan should be defined. The management context of the heritage site has then to be analysed to identify exogenous issues to the site's condition. A third phase should focus on defining the cultural significance of the place and, as a matter of fact, the reasons for the conservation of its tangible and intangible features. The identification of the features of significance and the heritage value associated plays a key role in the conservation process since decisions related to the conservation of such assets will be made accordingly. This step requires attention to guarantee the efficiency of the method proposed. We plan to automate a set of actions leading to the preventive detection of threats that might affect the condition of features of significance. Then, we present a method that suggests taking advantage of Fredheim and Khalaf's framework for the identification of these values [11], to further structure and integrate such data in the HIS. In addition to the gathered information, the documentation phase, by collecting the existing stock of information about the assets, allows stakeholders to better determine their needs in term new data acquisition. This final step of the analysis phase permits, through documentation and recording activities, to produce the necessary documents to understand and represent the physical condition and vulnerability of the site. Based on the analysis of present disturbances, effects or damage, and an analysis of any existing maintenance mechanism, past agents of deterioration can be identified. Also, the analysis of observed defects and the understanding of the underlying mechanism allow identifying risks related to the physical condition of the site.

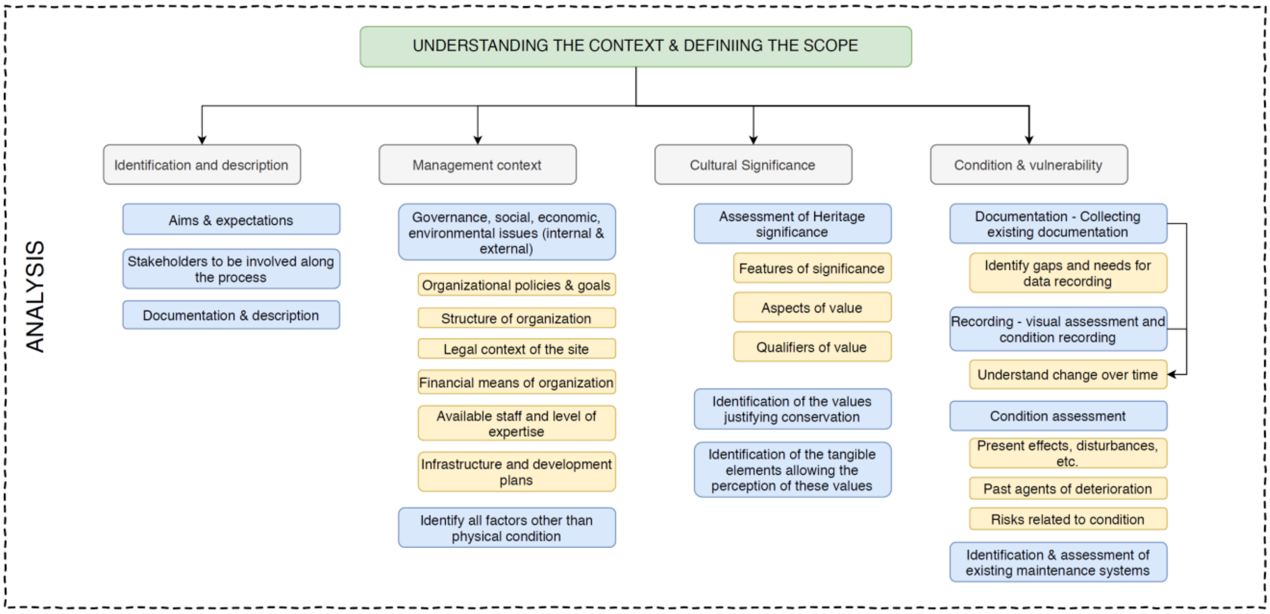

Figure 1. ANALYSIS: the first phase of the management plan process.

3.2. *Diagnosis*

The main goal of the diagnosis phase (Figure 2) is to provide relevant and accurate information about the underlying causes of all observed defects and provide the necessary basis for experts to propose the most appropriate remedies. Issues related to the managing context, such as the availability of resources (human and financial), the future needs of the users and stakeholders involved, possible constraints and obligations, the legal context, etc., must also be highlighted. In addition, potential future risks and their possible negative effects on features of significance should be forecasted. Together with the diagnosis and prognosis of defects, experts should provide stakeholders with clear "*recommendations for the most appropriate course of action having regard to the building, its future and resources available*" [26]. As a matter of fact, the impact of identified existing and potential future defects has to be assessed at this stage to assist stakeholders establishing priorities for maintenance works. According to Malcolm [27], risk assessment techniques can be applied to evaluate the impact of potential future failures, considering the likelihood of the defect to happen and its potential effects. Though the former criteria aims at defining the probability of the risk to happen and its frequency, the latter intends to establish the defects' consequences on the statutory compliance and/or functional suitability (regarding performance, function and users' requirements) of building elements. This information will help identifying essential (e.g., when a failure affects the structural soundness of a building, or when a building does not comply with fire safety regulations) and desirable interventions (e.g., fault in the design impacting the comfort of users). From this perspective, and in the case of heritage sites, the impact of these failures on features of significance of the site, and indirectly on the perception of the associated heritage values, the speed of deterioration of these valuable features must be considered. The significance of the building elements affected by the defects will then considerably influence the prioritization of some interventions over others.

Considering that preventive conservation strategies have progressively been recognized as more appropriate because less harmful to places of significance than curative approaches, the detection of existing and potential risks and the assessment of their possible impact is paramount when elaborating the management plan for their conservation. Moreover, these two steps particularly condition the successful implementation of the Digital Twin method to support preventive conservation strategies. At the end of the analysis (step 1) and diagnosis (step 2) phases, experts employ all necessary information in order to elaborate appropriate strategies for the preservation of their assets.

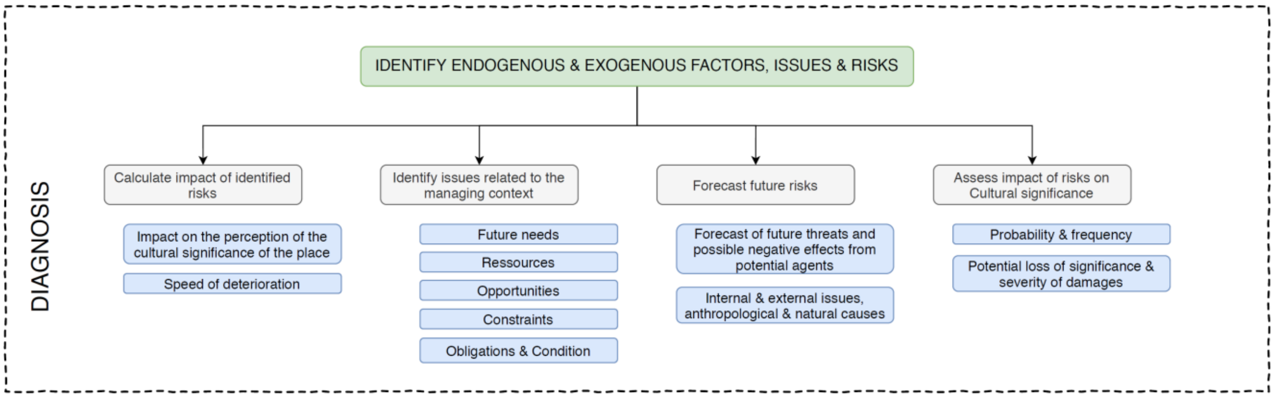

Figure 2. Diagnosis: the first phase of the management plan process.

3.3. *Therapy*

In the third phase, the reasons for the management and conservation of the site should be clearly defined based on the conclusion of the first steps (Figure 3). After having defined what should be preserved and why, the elaboration of policies will establish the global framework to define how the established objectives can be reached. To tackle the issues identified during the second stage, Conservation strategies with specific interventions can be elaborated in details and planned according to the estimated resources (financial, technical, human, etc.) and time needed for the execution of the conservation activities. At the same time, considering the need for risk preparedness in the framework of such processes highlighted earlier, mitigation strategies to limit the effects of potential defects and slow down the decay process of the site have to be defined. Furthermore, an evaluation of these strategies must be performed to raise decision-makers' awareness about, on the one hand, the level of uncertainty of the calculated effects versus the magnitude of the risk at stake and, on the other hand, the relation between the cost and the possible benefits of the suggested policies.

The method suggests that the automation of some monitoring tasks makes the whole process more efficient and reliable, through the use of a sensor network to monitor specific factors. When elaborating mitigation strategies and estimating their cost and efficiency, it is then important to identify the variables to monitor, define the thresholds, trigger values for the preventive detection of potential damages, determine the method and tools used to capture, follow-up and store the information and perform a cost/gains analysis. Once all these steps have been completed, experts and decision-makers can elaborate the strategic implementation plan based on a prioritization of the risks and on the availability of resources.

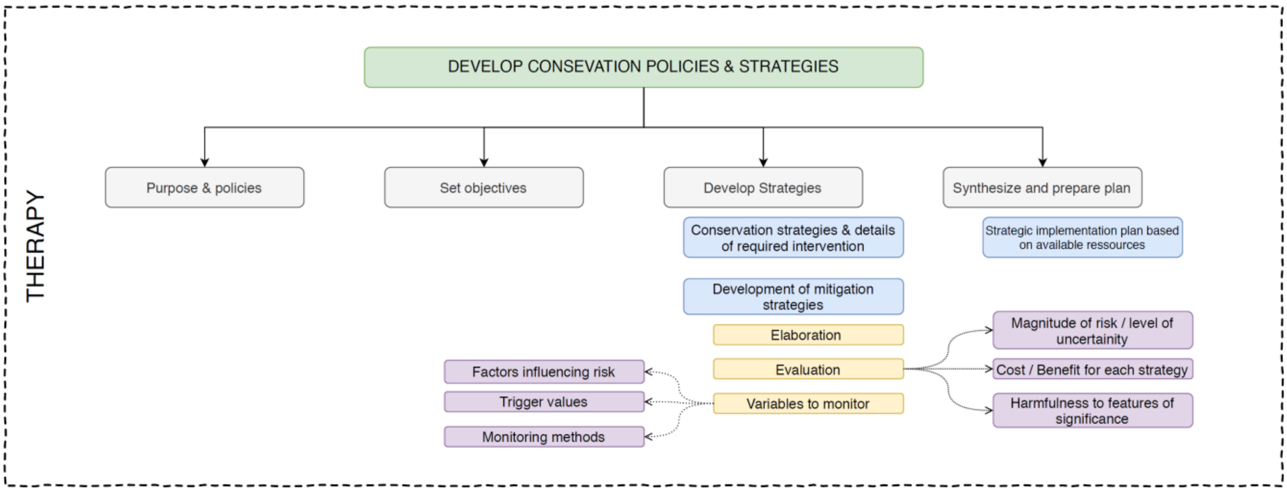

Figure 3. Therapy: the third phase of the management plan process.

3.4. *Control*

The last phase (Figure 4) of the process concerns the actual implementation of the conservation activities scheduled in the management plan and the monitoring of the efficiency of adopted solutions. This control makes it possible to detect inappropriate interventions and to review/adapt the strategies accordingly. It will be further proposed to take advantage of the Digital Twin to support monitoring activities and to provide decision-makers and site managers with tailored information for the preservation of their assets, by generating alerts in case of a threat, proposing adapted actions to mitigate their effects and monitoring the efficiency of the solutions implemented. Monitoring the effects also helps in identifying successful actions, and generating statistics and a complete history of the site's management in order to provide future stakeholders with a comprehensive understanding of the site, its context, and its evolution.

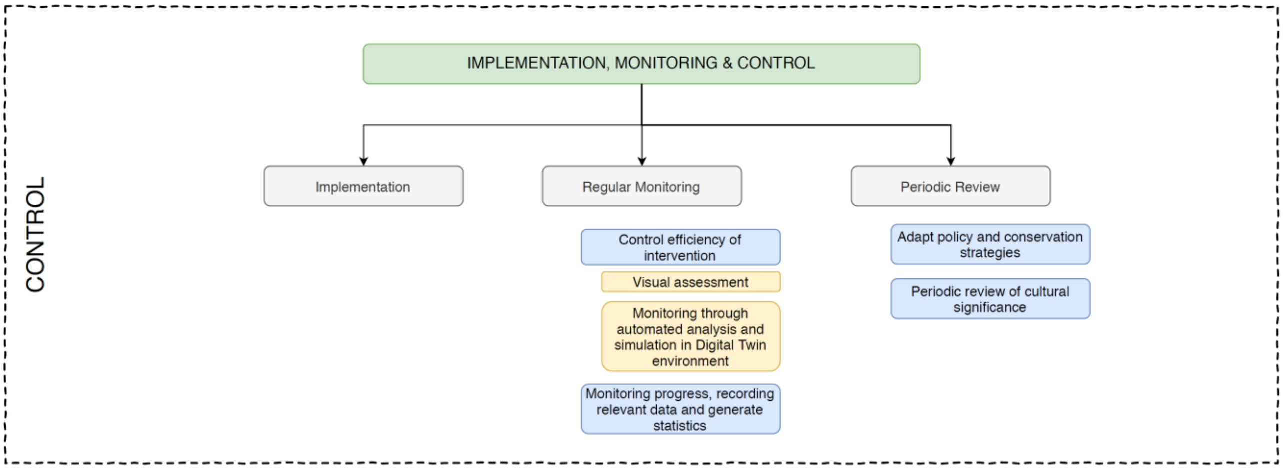

Figure 4. Control: the fourth phase of the management plan process.

Even though this conceptual model provides a framework for the establishment of management strategies for the preservation of heritage places, the application details have to be tailored to each specific application case. The process must be considered as a continuous loop among these four main steps, and completely contrary to a linear method (Figure 5). For instance, the forecasting of future potential threats or even the development of mitigation strategies, respectively in the diagnosis and therapy phases, might require the recording of additional data and take the experts back to the first step.

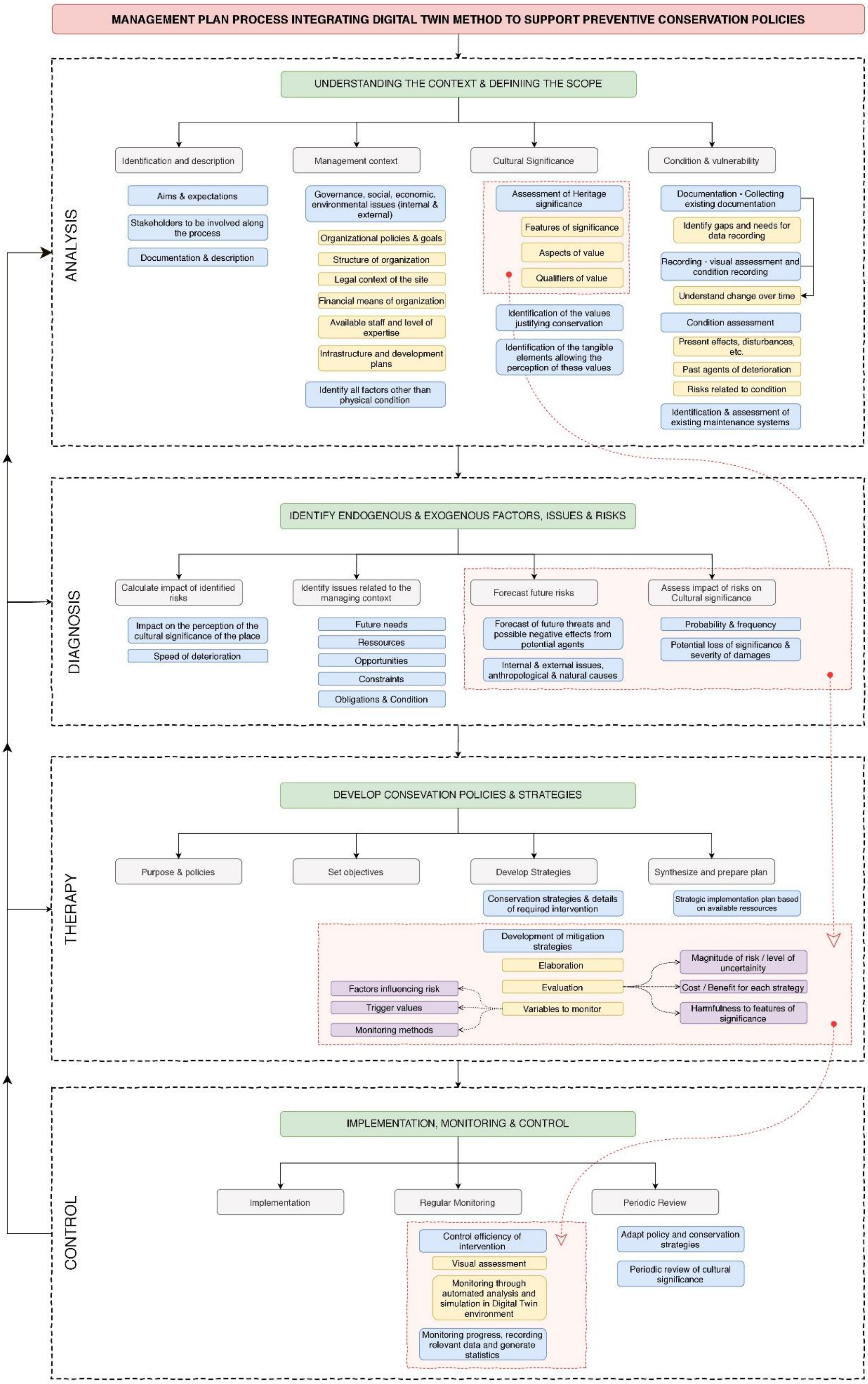

Figure 5. The complete value-based risk management plan process. The phases highlighted in red are the key steps towards the implementation of the method, further discussed in the next chapter (Section 4.2).

4. Digital Twin: A HBIM-Based Comprehensive Method for Supporting Preventive Conservation Strategies

4.1. Data management in DT environment

The HBIM models represent a relevant alternative for the collaborative management of information related to built heritage and to support conservation. Yang et al. [19] considered hybrid solutions to manage, on the one hand, the geometric features of heritage sites and their attributes through the use of HBIM parametric models and, on the other hand, the associated heterogeneous knowledge through more effective knowledge representation in ontologies. The latter could make it possible to capture the entire complexity of heritage information with all the interplay and relationships between the different data and allow stakeholders to extract key information performing complex queries. Several HBIM web platforms propose to link the geometric and spatial entities of the information model to a sensor network in order to monitor the evolution of specific variables, enabling the early detection of damage and the implementation of preventive actions. Automating the analysis and simulation of the real-time data provided by the sensors and comparing it to the information associated with the HBIM model, such a system could provide decision-makers and site managers with tailored information about the conservation of their assets in an efficient way (limited amount of time and reasonable budget). It is both profitable to these stakeholders and to the preservation of heritage places itself since the multi-criterion evaluation of possible intervention will include the impact of the latter on the cultural significance of the place. In this section, we explain the comprehensive method combining HBIM and DT principles. The three main components of this process, being the data input, the monitoring system in the Digital Twin environment and the data output, will be successively presented. This section will be concluded by a diagram depicting the complete DT process as a whole.

4.1.1. Data Input: Static and Dynamic Databases

The data input in the DT process consists of both static and dynamic data (Figure 6). The first category embodies the HBIM model, the knowledge, gathered along with the successive phases of the management plan process, associated with the geometric and spatial entities of the 3D information model and finally the standards adopted for the classification of risks, agents of deterioration, damages and possible treatments. The second type refers to the real-time operational information gathered on-site by the sensor network, as well as targeted data such as, for instance, weather forecasts to monitor specific risks associated with extreme climatic conditions.

First, it has been argued that commercial BIM solutions do not provide the necessary flexibility to fully represent the knowledge associated with heritage places due to the numerous and heterogeneous sources of information and several solutions have been proposed to tackle this issue, such as the use of open-source BIM software [50] and the combination of HBIM and ontology to separate the geometric information modelling in BIM software from the representation of all the complexity of the associated knowledge [19]. Diara and Rinaudo indicated that the data related to building elements of BIM models can be extracted from the IFC file by generating CSV (Comma-Separated Values) or XLSX (Excel spreadsheet extension) and subsequently "*stored and managed inside a relational or spatial DBMS*" [50]. In addition to the modelling of information related to heritage sites, open standards should be adopted for the identification of risks, damage and possible treatments to enable the awareness of DT with respect to their interrelationship and to ensure interoperability among the information systems of multiple organization and institutions. As a matter of fact, there is a need to develop an atlas of pathologies, treatments and agents of deterioration as an open standard, in order to improve interoperability of individual project databases and to ensure that all stakeholders share the same definitions. This approach enables information to be retrieved regarding the efficiency of treatments in specific contexts and sharing this knowledge so it can benefit to stakeholders involved in other projects.

Finally, the data input would also be fed by real-time operational data captured through the sensor network and transferred to the host server through a wired network or IoT wireless infrastructures. Based on the requirements of the projects, the specific deterioration processes or potential threats identified and the valuable features to be monitored to ensure preventive detection of potential damage, the sensors to be used and the thresholds or trigger values of one or several parameters can be defined. The monitoring and joint analysis of the different parameters can then be performed through commercial building monitoring software or web platforms. If many commercial and open source solutions to allow users managing the energy efficiency of their buildings already exist, there is a need for the development of open-source web platforms adapted to the heritage conservation context. The spreadsheets exported from the above-mentioned information sources can then be managed in DBMS to enable stakeholders to perform complex queries and retrieve tailored information for the preservation of their assets. As presented in Figure 6, the relationships among the different databases (management of geometric information, attributes and parameters of building elements in BIM software (1), knowledge representation in ontologies (2), building pathology standards (3) and real-time operational data (4)) are made using the unique HBIM identifier of building elements. In this regard, it is of high importance to define in advance the classification standards that will be used to structure and name these elements. The identifier makes it possible to link them to any relevant information such as the heritage values that have been attributed, the present condition, the threats that might affect the perception of their significance, and corresponding mitigation strategies. As suggested by Palomar et al. [20], a Common Data Environment (CDE), preferably in the form of a web platform, should be adopted for hosting, editing, and keeping the information contained in the model and associated databases up-to-date, but also to ensure the diffusion of the appropriate data to the relevant stakeholders at the right time.

4.1.2. A Process in the Digital Twin's Environment

The main objective of a Digital Twin is to help to predict specific performances through data acquisition, analysis and simulation. As illustrated in Figure 6, the Digital Twin process proposed first monitors the evolution of the parameters previously identified on the basis of the data provided by the on-site sensor network. Once the defined thresholds have been reached, an alert is generated identifying a potential threat to the integrity of the site and assessing its possible impact on the tangible features of significance. Depending on the issue detected, curative or preventive actions to slow down the decay and prevent/limit its effects can be suggested and their impact on different aspects (finances and other resources, timing, sustainability, potential loss of significance, etc.) can be assessed. On this basis, decision-makers can opt for the most suitable actions to implement and monitor their effects to evaluate their efficacy. The detection of new pathologies, the identification of new threats or the adoption of mitigation strategies could lead stakeholders to re-evaluate the efficiency of the sensors in place and adapt the network according to their evolving needs and the challenges faced. Statistics can be progressively derived, providing the system with data from field experience to adjust and improve the efficiency of the assessment of the potential impact of conservation activities.

4.1.3. Data Output: A Report for Decision-Makers

A direct operational document with very practical considerations can be generated from this process. The most outstanding output with direct benefits to the preservation of the place is obviously the elaboration of a report providing decision-makers and site managers with tailored information for the preservation of their assets in a very short time. Stakeholders involved at this stage rarely have the time nor the necessary knowledge to gather the required information, analyse and interpret the results to make the appropriate decision. Reducing the time lapse between the detection of the pathology and the intervention is crucial to limit the effects on the condition of valuable elements of the place and reduce the costs linked to the intervention.

If the results provided in the report are not clarifying enough, decision-makers will know which experts should be consulted directly, and the information already available in the database would limit the need for extra data acquisition. The report would include the identification of the threat and the tangible/intangibles features of significance affected, the relative importance and the magnitude of the risk, the potential effect of the mitigation strategies proposed specifying the level of uncertainty, and the impact of the suggested interventions on various factors such as finances and other resources, timing, sustainability, potential loss of significance, etc., thanks to the multi-criterion evaluation. The statistics generated after the monitoring activities can be imported in the static databases to increase the efficiency of the simulation and assessment process (Figure 6).

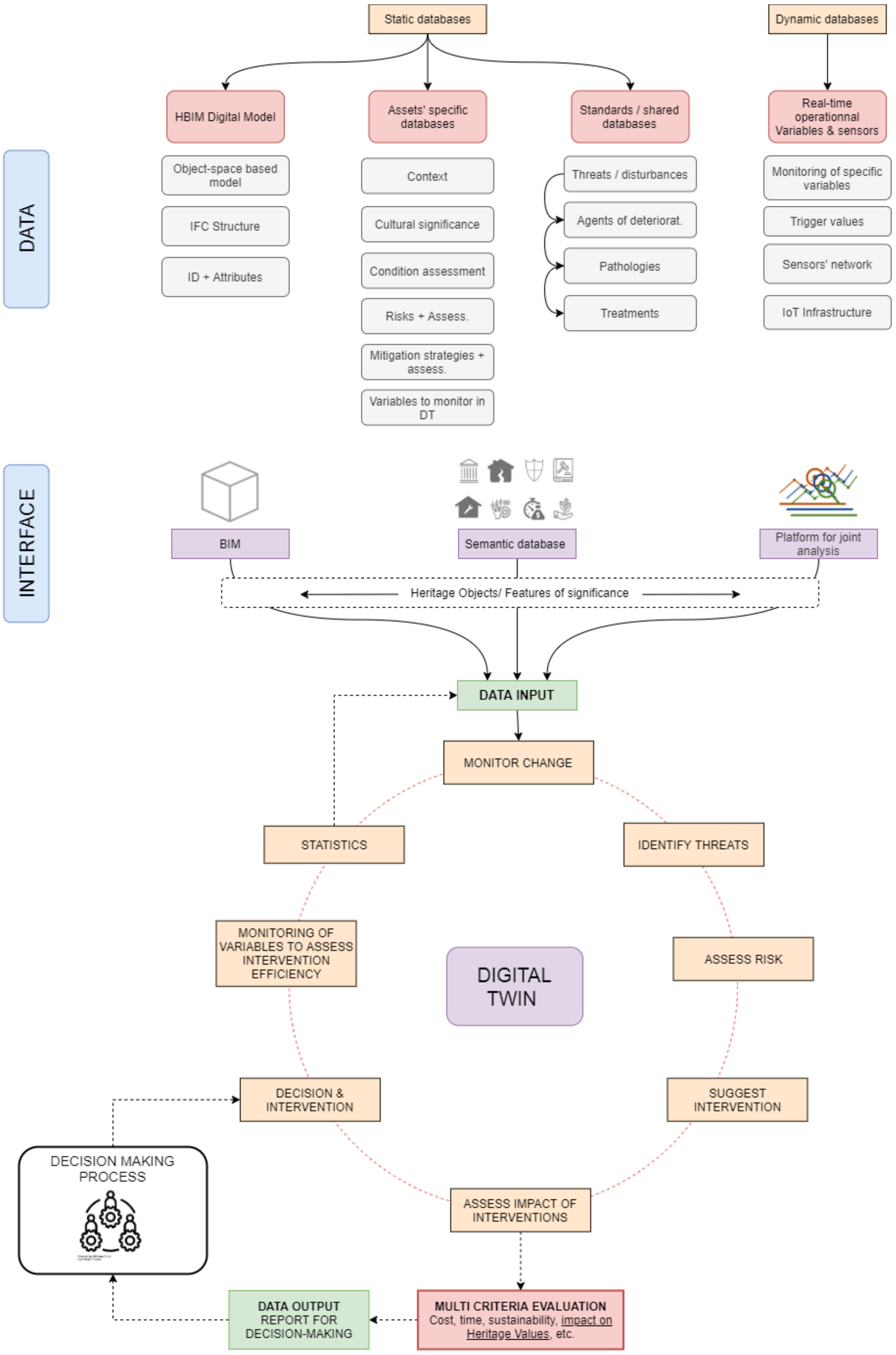

Figure 6. The Digital Twin process to support preventive conservation strategies for the preservation of heritage places.

4.2. Rules for Implementation of DT in Conservation Management Plan Processes

An important aspect predicating the successful implementation of such a method partly lies in its integration with the management plan process from the early phases onwards. As illustrated in Figure 5, the Digital Twin does not have to be considered as a punctual solution, but rather as integrated into the ongoing conservation management process. During the elaboration of the management plan, several steps require extra attention to ensure the workability and sustainability of the process. The key principles towards the implementation of the method presented in this article, highlighted in Figure 5, are discussed in this section. First, the identification of tangible elements associated with significant heritage value is paramount to establishing sensitive and sustainable conservation strategies. This initial phase then allows a better definition of the threats that might affect the valuable features of the asset and, as a matter of fact, cause a certain loss of significance. The greater awareness about the potential harmfulness of the identified risks on heritage objects also enables stakeholders to better define the processes and parameters to monitor in the DT environment. Finally, the actual monitoring of the asset's decay and of the identified key variables makes it possible to control the effects of implemented solutions, adjust the latter if necessary, and adopt additional preventive measures if required. Through the management of data related to each of these specific stages and its structuring in the data models and databases, it can further be properly interpreted in the Digital Twin environment, which will be dealt with in this section, with a particular focus given to the identification of features of significance due to the importance of this specific stage with respect to the complete conservation process.

4.2.1. Cultural Significance

A multi-criterion evaluation of risks and corresponding preventive solutions, with an awareness of the cultural significance of heritage places, is suggested in order to provide tailored information to site managers and decision-makers for the conservation of their assets. Considering the constantly evolving scope of Cultural Heritage and the complexity of capturing all meanings and interpretations to assess its significance, "encoding" the latter in HIS in such a way that it can be understood and interpreted in automated analysis and evaluation processes appears challenging. It requires the logical structuring of elaborated statements supported by a wide variety of sources, and thus implies a certain simplification. To achieve such a task, this article suggests the application of the three phases of Fredheim and Khalaf's framework for the value assessment of heritage sites. Apart from the fact that it will help to gain a more complete understanding of the significance of heritage assets, it will foremost facilitate the structuring of such information and, as a result, its integration in HIS. Hereafter, it will be explained how, in the case of the built heritage, useful data can be extracted from each of these three stages and integrated into HBIM data models in a way that guarantees the potential interpretation of this information by automatic analysis and evaluation processes.

The tangible heritage objects identified after the first phase can be associated with the corresponding spatial entity or geometric elements of the assets' HBIM model. In fact, adopting the structure of the IFC format (project, site, building, building storey, building element, building space) to organize/structure the different scales of heritage sites and objects appears logical for preparing the merging of semantics in the data model. Identifying the tangible features of significance is crucial to enable the Digital Twin process to make the link between the different databases (Figure 6) and, as a matter of fact, to associate these heritage objects with the corresponding values, risks, and so on.

The brief description of the values or the reasons for the significance of these features cannot be used as quantitative data in the Digital Twin method. However, when providing decision-makers with an analysis report concerning risk to the integrity of a valuable element, integrating such a description for the elements concerned is particularly interesting since it allows the stakeholders to quickly understand the values associated with the object and the context of its assessment.

In the final stage, the relative importance of the heritage objects can be assessed using Fredheim and Khalaf's qualifiers of value. While, on the one hand, authenticity (defining the truthfulness of heritage depending on the credibility of information sources) and rarity are particularly helpful qualifiers to assess the relative significance of valuable features, analyzing the condition of these tangible elements helps to define how perceivable are the corresponding values. This over-simplification, leading to relative quantification of the importance of specific features, is a key step to ensuring awareness in the Digital Twin process of the significance of the site and its components and enabling experts to communicate implicit conservation decisions to non-expert stakeholders. As will be expressed in the following section, this data is also very useful for assessing the magnitude of the risks. The class diagram underneath (Figure 7) illustrates the elaborated workflow for the structuring of such complex data in HBIM models.

We recommend extracting key information from the value assessment taking advantage of the framework proposed by Fredheim and Khalaf. On this basis, a process is proposed to facilitate the structuring of this data in HBIM models organized around the tangible heritage objects/features of significance. The latter is associated with the heritage site to which it belongs and is given a category in a first stage. Then, the values associated with each feature can be associated as well as a brief description of the reasons for their significance. The perceptibility of these values through the observation of the corresponding heritage objects should then be assessed using the qualifiers of value to finally enable stakeholders to assess the relative importance of the features in question.

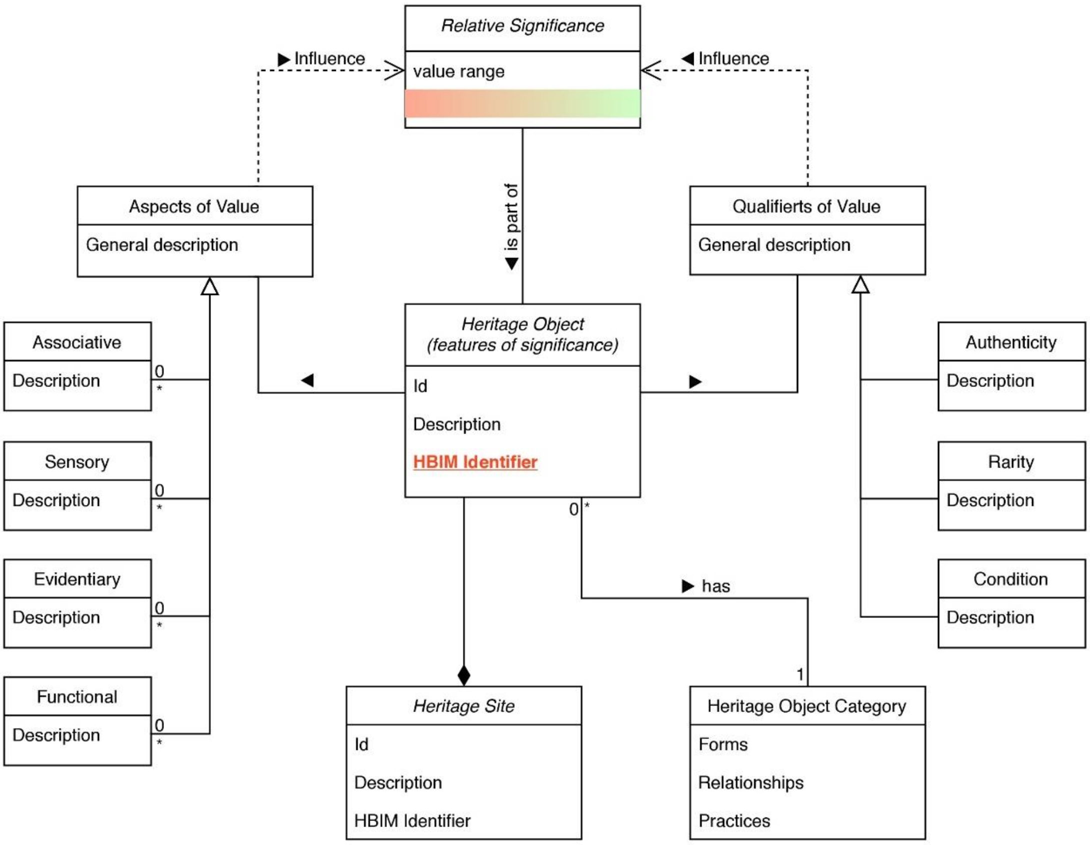

Figure 7. Conceptual model proposed for the structuring of heritage objects' significance in data models. At the centre of the model, the heritage object, contained in one or several heritage sites, has to be associated with the appropriate category. Then the description of the associated values and the general significance of the elements have to be provided. Together with the qualifiers of value, which enable evaluating the perceptibility of each value, they help stakeholders to define the relative significance of the heritage object using a value scale.

4.2.2. Identification of Risks and Assessment of Their Impact

The ongoing deterioration processes and future possible threats to heritage objects' integrity previously defined need to be analysed to enable experts to determine the parameters that need to be monitored in the control phase. Furthermore, the importance of the risk must be assessed when considering the likelihood of the defect happening and its possible consequences. Experts can then generate quantitative data through this process by applying a "scoring system to rank the different risk in a matrix" [27] according to their magnitude and, by doing so, assist the stakeholders in prioritizing interventions. Paolini et al. proposed a tool for assessing the magnitude of the risks (Figure 8) based on three aspects: the frequency of a risk's occurrence, the degree of loss of significance, and the portion of the site affected. A quantitative result defining the risks' magnitude is then obtained by attributing to the risks a value for each criterion which, in this method, all have the same weighting with respect to the final risk magnitude assessment (33.33%).

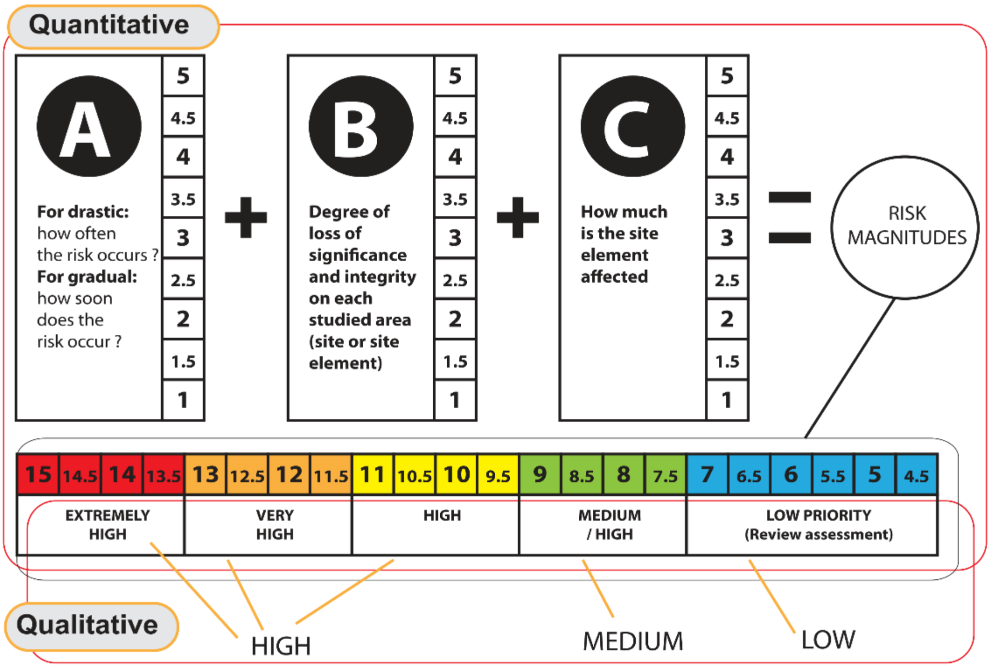

Figure 8. The evaluation method proposed by Paolini et al. in 2012 [10].

While it has been argued that quantitative data defining the relative importance of the risks to heritage sites should be generated to allow experts to "*rank these risks in a matrix*" [27], this research suggests that the importance of each criterion should be balanced and more importance should be given to the potential loss of significance. Indeed, a failure might occur on a very rare basis and affect a very small portion of the site, but this part of the asset might contain extremely valuable features of significance and the effects of the risk could be extremely devastating. The global magnitude of such a risk, applying the suggested method, would then be moderate to low, while the potential loss of significance would be considerable. Considering the method proposed by Paolini et al. not to be entirely appropriate, we suggest a review of this model in further research.

In terms of data requirements in the DT process, after having assessed the values of the heritage object, the ongoing and potential threats to their integrity have to be identified through condition and risk assessment, defining respectively existing pathologies and past processes of deterioration on the one hand and, on the other hand, the potential future risks. As expressed in the conceptual model (Figure 9), the relationships between the data is centreed on the heritage object. Once identified, the risk magnitude should be specified considering the probability of the hazard to occur and its potential effects on the building, such as the loss of significance it could result in for instance.

Attributing a value to each criterion makes it possible to determine a relative magnitude of the risk, but attention should be given to the method leading to their weighting in the evaluation process. On this basis, analysis and simulation processes conducted at the end of the (cyclical) process would then be able to retrieve the necessary information to prioritize the need for intervention and elaborate different conservation strategies scenarios (see Section 4.2.3.).

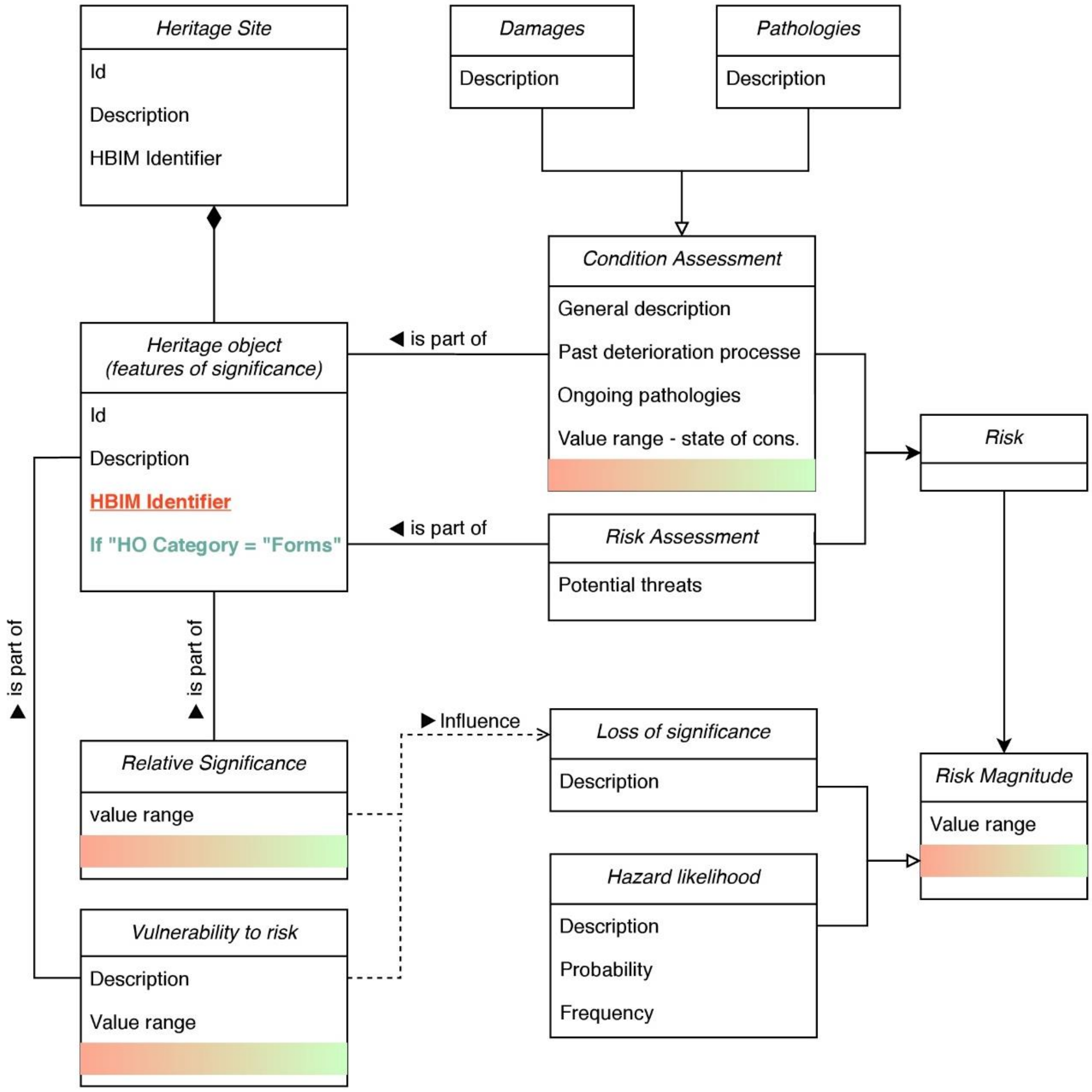

Figure 9. Structuring of data for the risk assessment centreed on a heritage object. The HO is associated with specific threats to its integrity (determined by risk and condition assessment) and a relative value is given to the magnitude of the risk (affected by the probability of the risk, the potential loss of significance (influenced essentially by the significance of HO and its vulnerability to the risk) and the portion of the features impacted.

4.2.3. Mitigation Strategies and Impact Assessment

On this basis, conservation strategies can be elaborated to mitigate the effects of the risks specifying, according to Paolini et al. [10], preventive and curative conservation actions at different levels of control. Among the preventive methods, monitoring the evolution of targeted variables to allow the early detection of deterioration processes resulting from identified threats is, when applicable, the most suitable, and allows the implementation of less invasive or destructive actions to avoid or limit the loss of significance. Once the most significant risks have been highlighted and corresponding strategies for mitigating their effects elaborated, the efficiency of the latter still needs to be assessed (Figure 10) through a cost–benefit analysis. This evaluation will allow the Digital Twin to propose intervention and evaluate their pertinence considering not only the emergency need for intervention, but also the economic reality of the managing organization. Another important criterion to consider when assessing the importance of risk and estimating the benefit of possible interventions is the reliability of the quantitative information on the basis of which the evaluation is performed. The assessment of the risk magnitude and the efficiency of preventive and curative actions must then be relativized based on the level of uncertainty of the available data. A high level of uncertainty does not decrease the importance of the risk, but rather gradually increases the necessity of further research as the magnitude of the risk increases. Finally, the evaluation process of the mitigation strategies should consider the impact of the latter on the preservation of features of significance. Indeed, the conservation of valuable heritage objects in buildings is increasingly challenged by the constantly evolving performance standards for buildings. "*Adapting historic buildings to meet complex new performance standards is about managing change without jeopardizing the heritage that is being protected*" [58]. Reaching conservation and performance goals often leads to conflicting situations, since required interventions involve the use of intrusive/destructive techniques, leading to the irretrievable loss of valuable features of heritage buildings. As highlighted by Carroon, performance goals may persist, but the means of achieving them might evolve and "involve more sophisticated and less intrusive technologies". Considering the uniqueness of Cultural Heritage, its preservation should then prevail on performance goals and, consequently, intrusive and harmful intervention techniques must be avoided as far as possible.

Allowing automated simulation processes in DT to suggest and assess the efficiency of possible intervention to avoid, limit or treat the damages of any deterioration processes requires a certain awareness of DT with respect to the existing relationships among the agents of deterioration, their potential causes, effects and possible treatments. To do so, a standardized atlas of building pathology modelling the relationships between damages, agents of deteriorations and risk factors should be elaborated and adopted to ensure the interoperability and reliability of the information. Then, for each defect, possible interventions should be suggested in the database specifying the conditions under which the solutions should be considered (depending on the context of the damage, some interventions might not be appropriate), and the data required to confirm/inform the diagnosis (the recommendation of the Digital Twin could then include a suggestion for further analysis and research before implementing the intervention). The idea is to enable the early detection of damages/negative effects of deterioration processes through targeted systematic monitoring activities and associate the latter with the impacted tangible features.

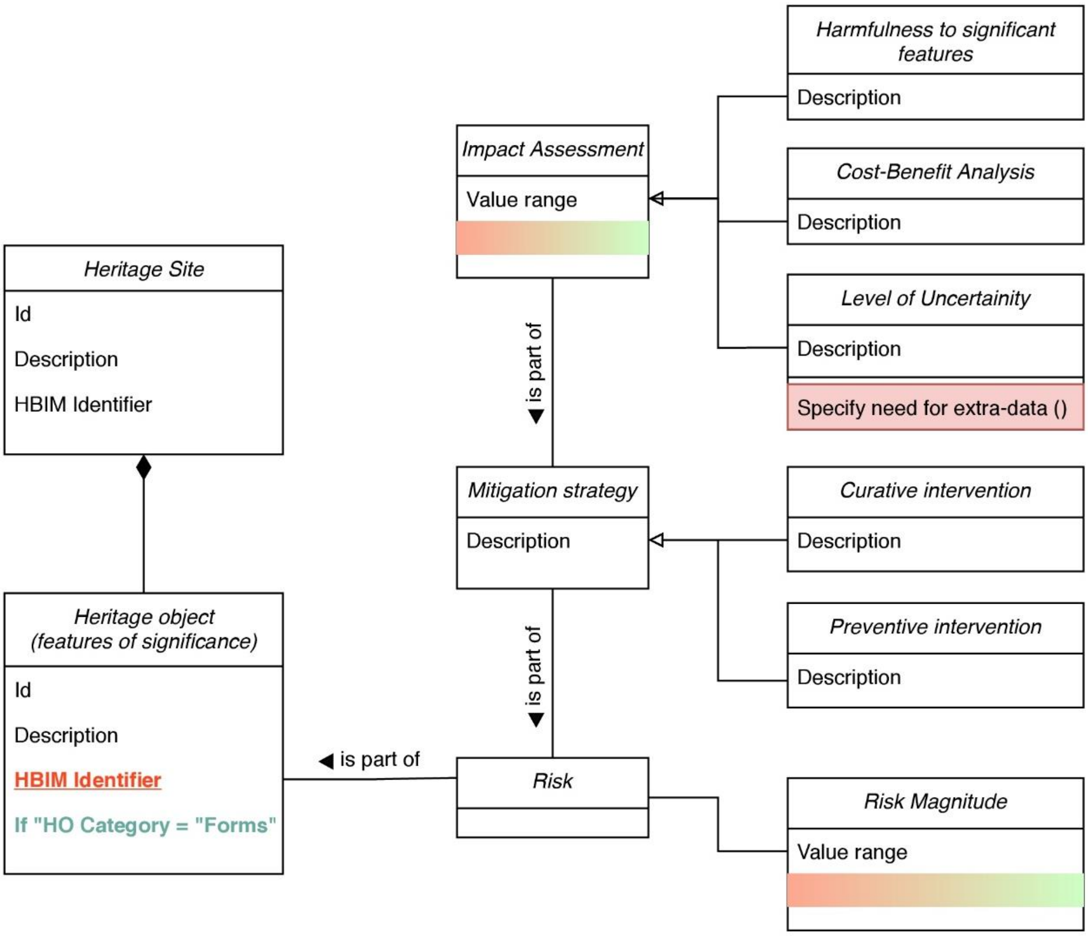

Figure 10. Elaboration and assessment of strategies to mitigate the effects of the risk. A risk is associated with several potential solutions (curative and preventive), the impact of which has to be assessed based on a cost–benefit analysis and relativized by the level of uncertainty of the data used for the assessment. The latter is particularly useful, since it indicates the need for the acquisition of additional information to decision-makers.

4.2.4. Implementation in the Control Phase: Sensor Networks and Multi-Criterion Evaluation

A network of sensors can be settled in heritage sites to monitor specific variables to control the evolution of ongoing deterioration processes, the early identification of imminent threats and the efficiency of implemented conservation actions and implement conservation actions accordingly. First, as shown in Figure 11, the parameters that allow the monitoring of these processes have to be highlighted before solutions to track these variables can be suggested and their efficiency assessed through a cost–benefit analysis. Then, trigger values have to be established either for a single parameter or a combination of several parameters (damage might occur under specific conditions and depend on several variables) to allow the generation of alerts when reaching the defined thresholds and launch the risk analysis and simulation in the Digital Twin to estimate the impact of the risk, suggest an intervention, estimate its efficiency and define the parameters that could be controlled to monitor the effects. Finally, in the final report providing tailored information to (often) non-expert decision-makers and site managers, the multi-criterion evaluation plays a key role in the process, since it allows taking a wider range of criteria to assess the efficiency of each solution. Indeed, in addition to the impact of the risks and the intervention on the potential loss of significance, considering the constraints related to the cost, the timing, the level of expertise, the human and material resources required, the sustainability, the reversibility, and so on (criteria have to be set depending on the context of the heritage site) would allow the report to place the results in a more global perspective. As a matter of fact, additional data has to be gathered depending on the selected criteria.

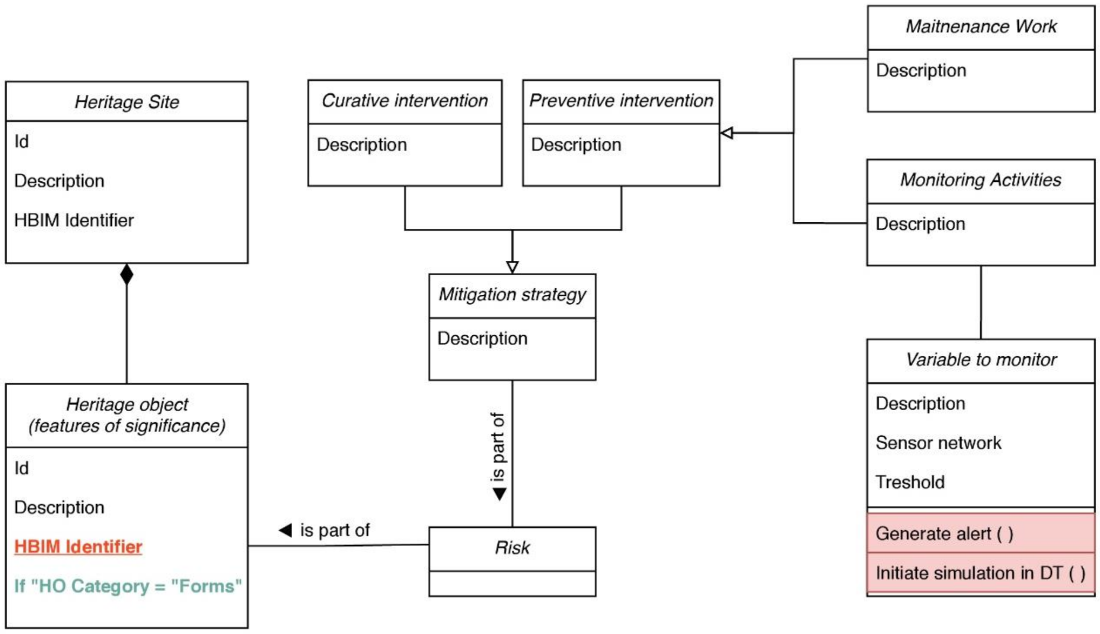

Figure 11. Initiation of simulation processes in DT through alert generation based on the monitoring of specific variables to monitor processes of deterioration or allow the early detection of hazards. The alert is generated after reaching the defined thresholds. .

5. Conclusions

This work highlighted the benefits of implementing the Digital Twin for the preventive conservation of the immovable heritage. Through the combined used of semantically enriched HBIM models as digital replicas with real-time operational data provided by on-site sensors through IoT infrastructures, the DT method strengthens the link between the digital model and the physical realm of heritage assets to provide tailored information to non-experts stakeholders involved in the decision-making process for the management of heritage places. Compared to current approaches to support preventive conservation policies, such as 3D GIS tools [7], for example, the main interest of this method lies in the automation of certain tasks in the early detection of threats to the integrity of valuable tangible features, the assessments of the risks' magnitude, the identification of possible solutions and the assessment of their impact. Thus, the application of DT principles in such a framework makes it possible to reduce the time required to acquire the necessary information for decision-makers, to slow down the decay and limit the negative effects of failures, to prevent or at least attenuate the corresponding loss of significance, and to minimize the cost of conservation work by reducing the need for intervention. In short, the method proposed in this research allows for a more effective preservation of heritage places by making non-expert stakeholders more aware of their importance during the maintenance phase.

We advocate the use of semantically enriched HBIM models as the digital replica of the DT process. It has been argued that although digital representation of heritage elements and their state of preservation can be achieved in commercial BIM solutions, capturing the complexity of the knowledge and meanings associated with the tangible features of significance requires the adoption of hybrid solutions using, for instance, ontologies to manage semantic information. The merging of this information from distinct environments can be achieved through the use of significant objects/legacy elements This is why we have stressed the importance of data structuring, especially for the classification of the geometric and spatial characteristics of heritage assets in such models; to allow the DT to link the different databases and to associate each material element carrying heritage values with the ongoing deterioration processes and potential threats to their integrity. Given the importance of heritage values in decision-making processes during the conservation process, we suggest their integration into data models and data flows. Based on the three main steps of the framework proposed by Fredheim and Khalaf, deconstructing the assessment process allows for the extraction of targeted information and its integration into HBIM models to ensure some awareness of the automatic analysis processes in the DT environment on the different key aspects of the values embodied in heritage sites. The heritage objects identified in the first step play a key role in linking the HBIM models to the semantic databases in DT. In this work, we emphasized the importance of integrating data flow management throughout the conservation management process in order to bridge the gap between the preliminary phases and the operation and maintenance of the assets.

This work represents the first achievement of a broader project. The next step consists of the model implementation on a concrete case study to evaluate and validate the suggested approach. Then, it was argued that the risk assessment method proposed by Paolini should be reviewed to better consider the potential loss of significance associated with identified risks when evaluating their relative magnitude. Although this method intends to support a more cost-effective and less harmful vision to the preservation of heritage valuable features, it requires a deep understanding of the place and its context, and implies significant work for the structuring of information in the data models. Despite the costs related to the implementation of such a method potentially being seen as a limitation, particularly for small-scale organizations; rather, it is necessary during the initial phases of conservation projects to pay increased attention to the early definition of specific objectives in terms of data needs.

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