From scan to H-BIM: towards an automated workflow for cultural heritage vulnerability assessment

Pietro Meriggi[1], Antonio Napolitano[1], Alessio Pasquali[1], Luca Bianchini Ciampoli[1]

[1] Roma Tre University – Department of Civil, Computer Science and Aeronautical Technologies Engineering, Via Vito Volterra 62 – 00146 Rome (Italy), {pietro.meriggi, antonio.napolitano, luca.bianchiniciampoli}@uniroma3.it, ale.pasquali3@stud.uniroma3.it

Abstract **– Originally designed for new buildings, Building Information Modeling (BIM) is increasingly being adapted to existing constructions with a focus on the 'as-built'. Heritage-BIM (H-BIM) addresses the complex reality of historic structures, characterised by irregular geometries, morphological defects, crack patterns and different materials, as well as fragmented documentation. However, there is a lack of standards and tools tailored for heritage conservation to equip H-BIM models with the typical characteristics of historic structures, exploiting the advantages of BIM in building heritage management. In this context, this study proposes a workflow to semi-automatically transform digital surveys into H-BIM models, enriched with detailed attributes - including structural defects and deterioration indicators - to support vulnerability assessment. With a focus on the conservation status of the monument, the final H-BIM output integrates the results of the vulnerability analysis, providing a comprehensive platform for heritage conservation and restoration planning, while improving data interoperability and decision-making in cultural heritage management. The methodology is applied to the case study of the Roman Arch of San Damiano, in the archaeological Park of Carsulae (Italy), for validation purposes.**

Keywords: Cultural Heritage, Heritage building information modeling (HBIM), Defects, Digital Survey, Parametric modelling, Vulnerability assessment.

I. INTRODUCTION

In recent years, the application of Building Information Modelling (BIM) to the existing architectural heritage has opened up new perspectives in the field of documentation, conservation and management of cultural heritage. Although BIM was originally conceived for new buildings and infrastructures [1], its evolution towards Heritage-BIM (H-BIM) has sought to respond to the specific needs of historic structures, characterised by irregular geometries, heterogeneous materials, cracks and stratified transformations over time [2-3]. In this context, the model is no longer a mere three-dimensional representation of the building, but takes on the role of a semantic and multidisciplinary digital archive, capable of integrating historical documentation, metric surveys, diagnostic data and information on transformations over time.

Unlike BIM for contemporary buildings, H-BIM addresses peculiar criticalities that require a profoundly different design and operational approach. Indeed, historic buildings have unique, non-standardisable components that are ill-suited to the predefined parametric libraries of BIM software. Moreover, data acquisition processes require advanced survey technologies (3D laser scanner, Structure from Motion, photogrammetry), resulting in high-density point clouds that, while offering extreme geometric fidelity [4], pose complex computational challenges in the modelling phase [5-6]. The survey-to-model (scan-to-BIM) conversion phase represents one of the central nodes of this digital supply chain, and still today sees a strong reliance on manual intervention, given the absence of fully automated tools capable of interpreting the morphological and material complexity of the historic built environment.

One of the main limitations of current tools lies in their poor ability to effectively represent and manage architectural pathologies and conditions of degradation. Modelling, often simplified for operational reasons, risks omitting information that is fundamental for the conservation of the asset, such as cracks, deformations and other indicators of vulnerability [7]. Furthermore, the integration of qualitative, diagnostic and stratigraphic data - indispensable for a complete historical and constructive analysis - clashes with the structural rigidity of traditional BIM software, designed for standardised information flows and oriented towards contemporary construction [8].

In the current landscape, research has highlighted some strategies to overcome such criticalities: from the customisation of information parameters, to hybrid modelling using mesh or NURBS surfaces, to the adoption of semi-automated methods for segmentation and classification of surveyed surfaces [8-12]. However, the

lack of a shared operating standard, the poor interoperability between different software platforms and the high learning curve of the tools used, continue to represent significant obstacles to the diffusion of integrated and replicable H-BIM approaches.

In the face of these critical issues, this paper proposes a structured operational flow for the integration, within an H-BIM model, of data concerning the state of conservation of a cultural asset, with particular reference to morphological defects and signs of vulnerability. The developed method includes a semi-automated pipeline, based on interoperable tools and a coherent classification of damages according to the guidelines of the Risk Map of the Italian Ministry of Culture [13]. The approach aims to transform the data obtained from digital surveys into rich, searchable and updatable information models, which not only support the monitoring of degradation, but also form a reliable basis for the sustainable management of historical heritage.

To demonstrate the effectiveness and practical applicability of the proposed methodology within a historical context, the paper presents its application to the case study of the Arch of San Damiano, a Roman construction situated in the Archaeological Park of Carsulae, in Italy.

II. METHODOLOGY

The proposed methodology (Fig. 1) consists of a structured and replicable workflow for the generation of an H-BIM model, designed to support the vulnerability assessment and management of cultural heritage assets. The objective is to develop a digital model enriched with semantic information, able to effectively organise documentation and integrate essential data for conservation, vulnerability analysis and intervention planning.
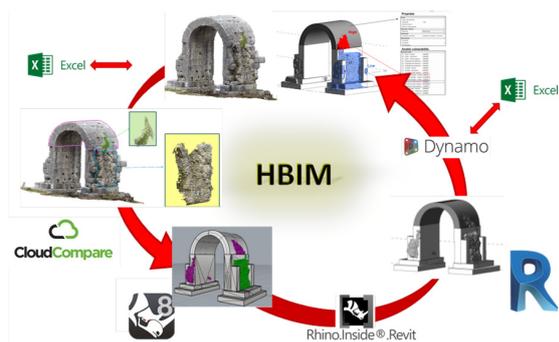

Fig. 1. The proposed methodology.

The methodology starts with the acquisition of the point cloud using digital survey techniques, which is then processed with *CloudCompare* software to identify and classify geometrical elements and defects. These form the basis for three-dimensional modelling carried out in

Rhinoceros 3D, equipped with plug-ins dedicated to the management of complex shapes, typical of historical architecture. The result is a simplified model of the structure, enriched with structural defects.

Thanks to the *Rhino.Inside.Revit* plugin, the 3D model is then imported in *Autodesk Revit* to obtain the final H-BIM model, which is integrated with information on structural defects. To this end, the guidelines of the Italian Ministry of Culture's Risk Map are adopted (§4.A). In particular, the identified defects are catalogued within a digitised database in *Microsoft Excel* format, which interacts with the H-BIM model through a *Dynamo* script for the semi-automatic assignment of vulnerability levels.

The overall process was designed to ensure fluidity and automation in the management of information. The result is an information model that is not limited to a mere geometric representation, but constitutes an operational tool for heritage management and vulnerability analysis (§4.B).

In the following paragraphs, the proposed methodology is outlined in more detail, highlighting the following two main areas:

1. the development of a digitised *Risk Map* for the calculation of vulnerability, with a focus on vulnerability related to the damage state of the building;
2. the implementation of an operational workflow for the constitution of the H-BIM model, equipped with the typical characteristics of historical buildings, including morphological peculiarities and the state of damage.

In practice, this methodology consists of the following steps:

- Digital survey and data import;
- Defect mapping and classification;
- 3D modelling from the point cloud;
- Conversion of 3D elements into parametric BIM components;
- Automatic assignment of H-BIM information - materials and vulnerability-related level to defects - into the information model.

A. Vulnerability assessment

As mentioned earlier, for the purpose of assessing the vulnerability of the structure, the *Risk Map*, developed by the Ministry of Culture (MiC), was adopted as the standard.

From this, only one Vulnerability Assessment Sheet was chosen, specifically the one referring to the State of Conservation of the monument, and a compilable digital database was recreated, which is an adaptation of the official guidelines.

In a brief summary, the database covers the following six types of defect:

- A: Compromise of structural integrity: which includes phenomena such as subsidence, out-

of-plumbness, buckling and disconnection;

- B: Disintegration and loss of material: which includes phenomena such as corrosion, surface disintegration and alveolisation, with progressive loss of compactness of the materials;
- C: Staining and moisture-related phenomena: including infiltration, condensation, salt efflorescence and water stagnation, which can lead to progressive degradation;
- D: Biological attacks: including colonisation by microflora (algae, fungi, lichens, mosses), infesting macroflora and attacks by insects or animals, which modify the surface and accelerate degradation;
- E: Alterations to the surface layers: with phenomena such as detachments, cracks, efflorescence, colour alterations and surface deposits (encrustations, vandalism, animal droppings).
- F: Partial or total absence of portions of the artefact: due to cracks, gaps, detachment of decorative or structural elements, such as falling tiles or pictorial films.

Defects falling into categories A, B and F mainly concern phenomena of mechanical and structural degradation or loss of material, directly compromising the stability or legibility of the architectural element. Such defects are therefore typically characterised by a subtraction of material, resulting in a 'negative' representation within a BIM model. In other words, the geometry of the ideal element, free of defects, must be modified to remove a portion corresponding to the pathology present.

Damage falling into categories C, D and E, on the other hand, are characterised by superficial and aesthetic alteration phenomena over time, where the elements are subject to interaction with external agents, such as environmental and biological factors, which weaken the material over time, but do not cause immediate structural impairment. Such defects are characterised by an alteration of the element, without a significant loss of volume. From a BIM modelling perspective, the representation can be:

- Neutral: when it comes to phenomena that do not modify the geometry of the solid, but only alter its surface perception (e.g. humidity, stains, salt efflorescence). In this case, the most appropriate solution is the use of textures to highlight the presence of the alteration without modifying the volume of the element.
- Positive: when the defect involves an increase in material, i.e. the addition of elements on the surface of the ideal model (e.g. biological colonisation by mosses, lichens, algae). In this case, the representation can be realised through the addition of meshed elements, which to all

intents and purposes have dedicated BIM information layers, superimposing new geometries on the original model.

Once the defect is identified on the structural element in question, the next step involves assigning the material type and three key parameters that define its significance:

- Extent, which describes the portion of the architectural element's surface affected by a specific pathology, classified according to percentage ranges;
- Urgency level, representing the priority with which the defect or pathology requires intervention, categorized as low, medium, or high;
- Severity, which describes the actual impact of the defect on the structure. This is assessed on two qualitative levels, based on factors such as the type and extent of the defect, its influence on the functionality or stability of the element, the risk to the overall integrity of the asset, and the potential for damage propagation over time or space.

All this information, entered into the digital database, is automatically transferred into the BIM model under development through *Dynamo* scripts (§II.B). The model is thus populated with all detected defects, precisely located on the structure, and equipped with information derived from the vulnerability analysis.

At the current stage, the methodology includes only types C, D, and E defects classified as Positive Representation. Work is ongoing to integrate all remaining cases.

B. H-BIM modelling workflow

The workflow introduced earlier is now described in detail, illustrating the methodological approach adopted step by step. The process begins with the collection of the building's geometric data by means of digital surveying, which allow high-density point clouds to be generated. This phase forms the basis of any as-built process and is commonly referred to as scan-to-BIM.

The acquired point clouds are then processed using *CloudCompare* software, which allows the data to be filtered, simplified and optimised, thus facilitating subsequent modelling and import into H-BIM software. In this phase, two sets of elements are identified and distinguished: on the one hand, the regular geometric elements ('basic' elements) that make up the structure; on the other hand, the defects or morphological anomalies, modelled separately as 'mesh' elements, as they cannot be reproduced with traditional CAD tools.

Once the point cloud has been optimised according to the design requirements, three-dimensional modelling is carried out. Modelling is carried out using *Rhinoceros 3D*, selected for its effectiveness in handling complex geometries thanks to the use of NURBS technology and a

wide range of advanced tools for technical drawing.

Once the modelling of the 'basic' elements has been completed from the tracing of the point cloud, the critical node of the representation of defects and non-reproducible elements ('mesh' elements) is tackled, which are treated as independent meshes.

The process consists of three operational steps:

1. Mesh creation: a local mesh is generated from the portion of the point cloud comprising the defect.

2. Import and editing in *Rhinoceros 3D*: The mesh is imported into *Rhinoceros 3D*, where the affected area is cropped using advanced editing tools.

3. Overlay and separation: the mesh is overlaid on the basic geometry and separated using the operator _MeshSplit. This allows the damaged portion to be isolated without geometric overlap, generating an accessory element that, once integrated into the BIM model, maintains geometric continuity and allows specific information such as materials, vulnerability levels and colour coding to be associated.

Once the modelling in the *Rhinoceros 3D* environment is complete, the model is converted to BIM format using *Rhino.Inside.Revit*, generating intelligent entities, correctly positioned but initially lacking detailed technical information. The adoption of the *Rhino.Inside.Revit* plug-in constitutes a strategic step, as it allows native integration between *Rhinoceros* and *Autodesk Revit*, overcoming the typical limitations of interoperable formats and guaranteeing a direct flow between the two platforms.

At this point the need emerges to structure the *Autodesk Revit* model for the management of attributes not foreseen by the original logic of the software, mainly in the conservation field. We therefore intervene with the definition of 'Shared Parameters', additional customised information fields that can be read, modified and exported according to interoperable logic.

The input of information, such as materials and vulnerability-related levels of defects, takes place in a semi-automatic mode thanks to the use of the visual programming software *Dynamo*, integrated in *Autodesk Revit*. The data is originally contained in a *Microsoft Excel* database, structured according to the guidelines of the Risk Map of the Italian Ministry of Culture, used to catalogue the pathologies detected during the physical or virtual inspections (as described in §II.A).

To support the interoperability between database and BIM model, three main *Dynamo* scripts were developed:

- Script for entering materials: reads and associates to each element the material indicated in the *Excel* database.

- Script for assigning defect parameters and colouring: automatically assigns Severity, Extent and Urgency values, and applies colouring consistent with the element's vulnerability index.

- Integrated script: combines the previous functionalities into a single automatic routine, optimising the entire process of populating the BIM model with information.

In this way, the final H-BIM model integrates simplified but faithful geometries, structured diagnostic information and an immediate chromatic visualisation of the state of preservation, meeting the requirements of interoperability, traceability and updatability inherent to built heritage management.

III. FIELD APPLICATION

A. The Roman Arch of San Damiano in Carsulae

The Arch of San Damiano is one of the most representative monumental elements of the ancient Roman city of Carsulae, today an archaeological site located in Umbria, central Italy. The structure, datable to the 1st century A.D. and built under the principate of Augustus, is built using blocks of local limestone arranged dry, according to traditional Roman building techniques. Of the original work, only the central archway survives today, set on two pillars of *opus caementicium* covered with large square blocks of opus quadratum, placed with extreme precision and without the use of mortar (Fig. 2). The round arch has a span of 5.0 m, a thickness of approximately 0.8 m, an overall height from street level of 9.2 m and a depth of 4.5 m. The base consists of three stone steps, with an overall width of approximately 6.0 m.

In spite of its extraordinary resistance over time, the arch today shows evident phenomena of degradation, mainly attributable to the prolonged action of atmospheric agents and the natural ageing of materials. Surface erosions and localised detachments have partly compromised the legibility of the stone face. In this context, the use of advanced digital survey technologies, together with information modelling using the H-BIM approach, offers new opportunities for the documentation, analysis and conservation of this significant archaeological artefact.

Fig. 2. The Arch of San Damiano, in Carsulae.

B. Application of the methodology

In this section the methodology described in §II is applied to the case study of the Arch of San Damiano for validation purposes, going through all the steps (Fig .3).

- Digital survey and data import: a photogrammetric survey was performed and the point cloud was obtained
- Defect mapping and classification: defects, including shape singularities, were selected and

measured on the point cloud, classified, and their data entered into the dedicated digital data base as explained in §II.A. In particular, in this paper the attention was focused on biological attacks (defect D), present on both the arch element and on the abutments, and material detachment (defect E), present on the abutments.

- 3D modelling from the point cloud: both 'basic' elements – the arch and the two abutments, and the 'mesh' elements – shape singularity (rests of *opus caementicium* on the abutments) and defects were modelled in *Rhinoceros 3D* starting from the point cloud, as explained in §II.B.

- Conversion of 3D elements into parametric BIM components: this step was carried out by means of *Rhino.inside.Revit* plugin, which can be found in *Autodesk Revit* in the *Rhino.Inside* tab, under the *Rhinoceros > Import 3DM* group. First the 'basic' elements (arch and abutments) and then the 'mesh' elements (singular elements and defects) were imported, the latter under the category 'generic models'.

- Automatic assignment of H-BIM information - materials and vulnerability-related level to defects - into the information model: thanks to the integrated *Dynamo* script, the results obtained through the vulnerability analysis are extracted from the *Microsoft Excel* digital database and automatically imported in the BIM model, to be visualised.

Fig. 3. Main steps of the validation of the methodology on the Arch of San Damiano case study.

IV. CONCLUSIONS

The paper presented a structured and replicable methodology for the generation of an H-BIM model to support vulnerability assessment and cultural heritage management. The proposed workflow starts from the digital survey and point cloud processing using *CloudCompare* software, to identify and classify geometric elements and structural defects. These are modelled in *Rhinoceros 3D* and subsequently converted into parametric BIM components through integration with *Autodesk Revit*, thanks to the *Rhino.Inside.Revit* plugin. The final H-BIM model is enriched with semantic data and structural defects, to which vulnerability levels are assigned through a semi-automatic system based on *Dynamo* scripts and interactive tables, in accordance with the guidelines of the Ministry of Culture's Risk Map. The entire process allows for a smooth and automated management of information, overcoming the simple geometric representation in favour of an operational tool for conservation and intervention planning.

The methodology was successfully tested on the case study of the Roman Arch of San Damiano, located in the Archaeological Park of Carsulae, demonstrating the effectiveness of the approach in documenting, analysing and managing the morphological peculiarities and the state of conservation of historic buildings. Future research developments will be oriented towards the finalisation of the digitisation of the Risk Map, with the systematic inclusion of all types of detectable defects, in order to further strengthen the accuracy and reliability of vulnerability analysis in cultural heritage contexts. In addition, work is in progress towards the setting up of a digital information platform also integrated with GIS-type cartographic data [14], for the smart management of the historic buildings.

REFERENCES

[1] L. Pallante, P. Meriggi, F. D'Amico, V. Gagliardi, A. Napolitano, F. Paolacci, G. Quinci, M. Lorello, G. de Felice, "An Integrated Data-Driven System for Digital Bridge Management," Buildings, vol. 14 (1), 2024, 253.

[2] S. Logothetis, A. Delinasiou, E. Stylianidis,

"Building Information Modelling for Cultural Heritage: A Review," ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., vol. II-5/W3, 2015, pp. 177–183.

[3] X. Yang, P. Grussenmeyer, M. Koehl, H. Macher, M. Murtiyoso, T. Landes, "Review of built heritage modelling: Integration of HBIM and other information techniques," Journal of Cultural Heritage, vol. 46, 2020, pp. 350–360.

[4] R. Yanez Chura, P. Meriggi, C. Choueiri, G. de Felice, "Seismic assessment of churches through integration of digital survey, texture recognition and distinct element modelling," Journal of Building Engineering, vol. 98, 2024, 111375.

[5] S. Brusaporci, M. Maiezza, A. Tata, "A framework for architectural heritage HBIM semantization and development," ISPRS Arch. Photogramm. Remote Sens. Spatial Inf. Sci., vol. XLII-2, 2018.

[6] M. Huang, J. Ninić, Q. Zhang, "BIM, machine learning and computer vision techniques in underground construction: Current status and future perspectives," Tunnelling and Underground Space Technology, vol. 108, 2021, 103677.

[7] L. Zhuo, J. Zhang, X. Hong, "Cultural heritage characteristics and damage analysis based on multidimensional data fusion and HBIM – Taking the former residence of HSBC bank in Xiamen, China as an example," Heritage Science, vol. 12, 2024, art. no. 128.

[8] A. De Falco, F. Gaglio, F. Giuliani, M. Martino, V. Messina, "An HBIM approach for structural diagnosis and intervention design in heritage constructions: The case of the Certosa di Pisa," Heritage, vol. 7, 2024, pp. 1850–1869.

[9] L. Barazzetti, F. Banfi, R. Brumana, G. Gusmeroli, M. Previtali, G. Schiantarelli, "Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans," Simulation Modelling Practice and Theory, vol. 57, 2015, pp. 71–87.

[10] D. Oreni, R. Brumana, S. Della Torre, F. Banfi, L. Barazzetti, M. Previtali, "Survey turned into HBIM: The restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila)," ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., vol. II-5, 2014, pp. 23–25.

[11] M. Murphy, C. Dore, "Integration of Historic Building Information Modeling (HBIM) and 3D GIS for Recording and Managing Cultural Heritage Sites," Proc. of the 18th Int. Conf. on Virtual Systems and Multimedia, 2012, pp. 369-376.

[12] X. Yang, L. Yi-Chou, A. Murtiyoso, M. Koehl, P. Grussenmeyer, "HBIM modeling from the surface mesh and its extended capability of knowledge representation," ISPRS International Journal of Geo-Information, vol. 8, no. 301, 2019.

[13] Carta del Rischio, Direzione Generale Sicurezza del Patrimonio Culturale, [Online]. Available at: http://www.cartadelrischio.beniculturali.it/document azioni. In Italian.

[14] G. Quinci, V. Gagliardi, L. Pallante, D.R.J. Manalo, A. Napolitano, L. Bertolini, L. Bianchini Ciampoli, P. Meriggi, F. D'Amico, F. Paolacci, "A novel bridge monitoring system implementing ground-based, structural and remote sensing information into a GIS-based catalogue," Proc. SPIE 12268, Earth Resources and Environmental Remote Sensing/GIS Applications XIII, 2022, vol. 122680H.