Integrating timber stability analysis for building life cycle management and HBIM framework support

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Abstract

The digital documentation of heritage architecture, particularly historic wooden roof structures, has gained significant importance in recent years. Heritage Building Information Modelling (HBIM) has emerged as a crucial field that focuses on the digital representation and management of historic buildings. However, modelling heritage structures in accordance with BIM standards poses challenges due to the complex geometries and specialized information inherent with heritage timber structure. This article presents a workflow that illustrates the integration of an automated, AI-supported analysis of wood knottiness to assess unknown strength values of aged heritage timbers within building life cycle management and supporting the BIM framework. For this purpose, an algorithm for automatic wood knottiness estimation has been developed and implemented as a smartphone-based app-prototype, which facilitates efficient data collection, automatic analysis, and seamless integration into the BIM modelling process, while minimizing potential data loss during exchange.

1. Introduction

The digital documentation of heritage architecture, e.g. historic roof structures, has become increasingly important in recent years. Modern acquisition technologies such as laser scanning or photogrammetry allow the rapid and precise capture of building geometry. However, the challenge does not end with data acquisition. An equally important question is how this data can be processed and stored in such a way that it can easily be shared and reused by different project stakeholders.

One common approach is to transfer the collected data into a CAD or BIM environment and provide it using the exchange formats required within the project environment. In many cases these formats include DWG-based CAD data or open BIM formats such as IFC. In this case, Heritage Building Information Modelling (HBIM), within the context of openBIM, is an increasingly important topic that deals with the digitisation and management of historic buildings and architectural monuments using digital twins. openBIM promotes software interoperability and information exchange between different players in the construction and planning industry. However, modelling aged timber structures according to BIM standards is challenging, as historical architecture often features complex geometries and subject-specific information that is difficult to classify. Usually, in openBIM the roof beams are represented by simplified cubes and defined by a few parameters, which are stored and transmitted alongside the broader data of a BIM model, using open formats such as IFC. The most important parameters (property sets) include geometric and alphanumeric information, addressing

- Geometry and dimensioning parameters (e.g. cross-section width/height, volume, position),
- Material and quality (e.g. wood type, strength class),
- Structural parameters (e.g. fire protection class).

However, in the case of aged heritage timber, a lot of additional information should be parameterised. This information is derived from optical analysis as well as timber geometry and surface features, what is usually omitted in openBIM. HBIM for timber structures involves a wide range of data that must be captured and managed, including structural, architectural, and historical data. However, complexity of timber structures makes modelling difficult.

Figure 1 demonstrates visual characteristics of an aged wooden beam, such as knots, tree edge and cracks, which can be used to estimate the unknown timber strength values and grading class.

The geometric complexity of historic timber structures makes them laborious and time-consuming to model using standard 3D software. The BIM-software often contains specific component libraries (e.g. Wood Structural Elements in Revit), which can be developed and refined further. In most cases, complex manual modelling is required and integrating additional information is not yet automated. In addition, a simplified cube representation is not sufficient in the case of aged timber, because even a geometric parameter such as the tree edge affects the stability of the beam and is not currently represented in the standardized BIM framework for new timber beams. Different physical and semantical properties, that should be taken into account during modelling, can influence the accuracy of HBIM models.

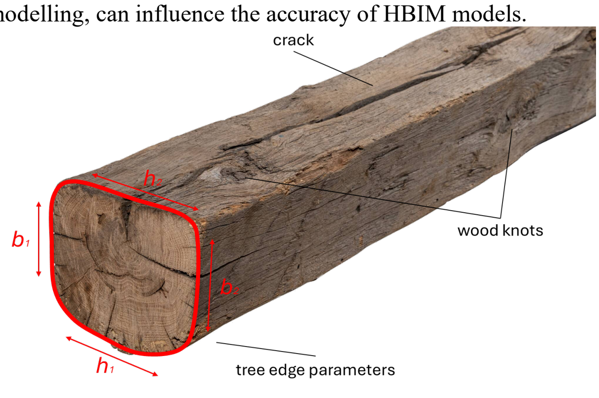

Figure 1. Parameters characterizing aged timber beam.

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In this article, we present an innovative workflow for integrating automated, AI-supported wood knottiness analysis for assessment of unknown strength values of aged heritage timbers into building life cycle management to support the BIM framework. For this purpose, an algorithm for automatic wood knottiness estimation has been developed and implemented as a prototype smartphone-based app. This app enables data to be efficiently collected, automatically analysed and transferred into the data modelling process within BauCaD software allowing data exchange with possibly minimal loss.

2. State of the art

Interoperability between different software tools and data sets is of great importance to ensure smooth integration into the HBIM system. It is crucial to choose appropriate standards that promote data exchange and compatibility. The necessity of moving beyond geometric modelling to include non-geometric information relevant to conservation and structural health stimulates discussion in heritage sciences and neighbouring disciplines.

(Santos et al., 2022) summarize the challenges, like more complex geometric and non-geometric structure of aged/heritage timber representation, involved in using HBIM for the restoration or preservation of historic timber structures in order to preserve original features while integrating modern techniques.

To overcome the challenges mentioned above, (Previtali et al., 2020) point out that the use of semantic web technologies is useful. These enable BIM models to be linked to external information from various ecosystems, with the data being captured by ontologies that allow flexible querying for different purposes (Cheng et al., 2021).

(Barontini et al., 2021) propose a structured workflow for damage assessment of historic buildings based on CIBSE PDT (Product Data Templates of Chartered Institution of Building Services Engineers) for standardising damage documentation in historic building elements and communication between BIM platform and PDS (PD Spreadsheets). They point out that the spreadsheet template should be predefined by mutual agreement between all parties, as the position of individual items of information cannot be changed and only the fields with parameter values can be edited. However, it is also possible that some PDT functions may not be readily available in the IFC schema.

(Wang et al., 2025) describes a KSQI paradigm that combines scan-to-BIM and rule-based reconstruction approaches (Knowledge, Survey, Quality, Information/Interoperability). In this process, purely geometric model information is separated from the underlying historical information/rules, with a view to recoupling them at a later stage. However, it is important to reiterate how a BIM team consistently facilitates interdisciplinary collaboration to incorporate specific information into the model, e.g. historical details, material specifications, evaluations of structural integrity and dendrochronological data. Therefore, it is crucial to implement a mechanism for ‘decoupling the model and data' during the initial phase.

(Argasiński and Kuroczyński, 2025) focus their research not only on the implementation of HBIM for the documentation and conservation of cultural heritage, especially on the creation of standardized templates for the Exchange Information Requirement (EIR) and the BIM Execution Plan (BEP), which serve as guidelines to promote broader implementation within the heritage science. In this case, open standards, such as IFC for geometry and semantics and the buildingSMART Data Dictionary (bSDD) for the classification mapping of cultural heritage assets, are used for the coordinated use, structured exchange and harmonisation of HBIM data. While free attribute assignment in the buildingSMART Data Dictionary (bSDD) for Heritage BIM (HBIM) provides the necessary flexibility for dealing with historical, non-standardised building components, it also presents significant challenges in terms of interoperability and data quality:

- Loss of interoperability and semantics: free-form attributes are often not recognised or are misinterpreted by other software applications.
- Subjectivity and inconsistent data structures, which can lead to ambiguity arising from different terms being used to describe the same phenomenon.
- The effort involved in mapping individual HBIM attributes to IFC standards, which requires specific expertise.
- Lack of standardisation in heritage conservation: The bSDD is designed to host standards. The representation of specific signs of deterioration, materials or historical construction techniques is often exceptional and difficult to fit into rigid standard structures.
- Technical limitations of authoring software: many BIM programmes do not support localised, free-form attribute definitions, which hinders their widespread application in existing buildings.
- bSDD governance rules: whilst the bSDD permits domain-specific extensions, it aims for ‘neutral, universal and reusable’ data. Project- or object-specific “free-form” entries do not correspond to the core purpose of the platform.

In this case, using IDS (Information Delivery Specification) in conjunction with bSDD could assist by specifying minimum requirements for data structures relating to the state of preservation, even though these must be stored as separate domain dictionaries within bSDD.

3. Method

3.1 Automatic approach for wood knottiness estimation

The precise identification of wood knots within historic timber structures is a single proof to estimate aged timber grading. Despite this necessity, the use of automated visual grading techniques for aged timber has been insufficiently investigated, owing mainly to factors such as irregular textures, weathering, and the scarcity of relevant datasets. Recent research conducted by Pan et al. (2025) introduced a comprehensive deep learning-based pipeline that incorporates the segmentation of timber beam boundaries, perspective correction, and knot detection to facilitate the assessment of wood knots (see Fig. 2).

Historic timber structures possess unique visual and material characteristics, including surface weathering, discoloration, biological degradation, and irregular geometries. As a result, existing datasets, e.g. presented by (Kodytek et al., 2021), are not well-suited for the analysis of historical wood surfaces, primarily because of the significant distinctions between knots in freshly cut wood and those found in aged timber.

To address the particular requirements considering radiometric and geometric complexity of heritage timber, a custom sample database has been developed within that project.

A comprehensive collection of raw data comprising over 10,000 high-resolution images of historic timber surfaces was assembled utilizing both DSLR cameras and mobile devices. This effort resulted in the creation of several datasets that include approximately 3,000 annotated samples, representing a wide variety of wood defects, ensuring robust training and evaluation of the models, namely YOLO, Detectron2, and DeepLabV3, using different experimental setups to allow

Figure 2. AI-pipeline for wood knot detection: RGB image (a), segmented beam side boundaries mask (b) applied on RGB image (c) and detected wood knots inside segmented boundaries (d).

for a comparative analysis of their performance in detecting and classifying wood defects.

3.2 Data integration

One aspect of the process is to capture data as effortlessly and accurately as possible; another is to find a method to process and store this data in a way that enables sharing and further use as simply and with as few compromises or restrictions as possible (i.e. barrier-free).
One common approach is to transfer the collected data into a CAD environment and provide it using the exchange formats required within the project environment. In many cases these formats include DWG-based CAD data or open BIM formats such as IFC.
Within this project, we first evaluated part of the building in 3D and then focused on defining strength classes and analysing them within our in-house software BauCaD.
Until recently, we worked entirely within the software environment of BricsCAD/AutoCAD, based on the DWG/DXF data structure. The DWG format has proven to be a very robust and flexible structure over many years and provides considerable freedom when extending objects with additional parameters.
A major advantage of this environment is the possibility of attaching custom attributes directly to geometric elements. For example, parameters such as strength classes, element identifiers, damage descriptions, or references to additional documentation can be stored directly with the respective building component. Within compatible CAD environments, this information can be exchanged reliably without additional adjustments.
Notable, the currently used DWG standard is still based on the DWG 2018 version. Despite this relatively stable version base, the format continues to offer a reliable and flexible structure for extending building elements with project-specific information. Within the DWG environment (AutoCAD, BricsCAD, Ares Commander), these data can be individually extended, and the range of possibilities is broad.
Once the data exchange leaves the CAD environment and the model is transferred to BIM platforms such as Revit or ArchiCAD, the IFC format is typically used as the exchange structure. IFC represents an open standard designed to allow building information to be exchanged across different software systems.
The IFC data model allows the storage of geometric information as well as basic semantic descriptions of building elements. At the same time, the possibilities for flexible extension and custom parameterisation are more limited compared to the DWG environment.
While IFC offers excellent compatibility for 3D data and metadata, it significantly limits the level of complexity and individual customization we can achieve.
These limitations become particularly relevant when dealing with specialised analytical information, such as the structural strength classification of timber elements in existing buildings as well as by increasement of geometric complexity of aged beams. Many of these parameters are not directly defined in the standard IFC schema.
Several approaches were investigated to transfer project-specific information between different software environments.

- The first approach is to store additional parameters directly as attributes attached to CAD objects. Within the DWG environment this method works reliably and allows the information to be transferred without loss between compatible CAD systems.
- A second possibility is to reuse existing BIM attributes within the IFC structure as placeholders for project-specific parameters. However, this approach requires agreement among project participants because the original meaning of the attributes is modified.
- A third strategy separates the detailed information from the actual 3D model. In this case each element receives a unique object identifier. The corresponding information is then stored in an external file, for example in CSV, XLS or TXT format. Using the object identifier, each element in the model can be linked to the corresponding dataset.

Our current approach is to create a 3D model based on openBIM classification and structure, linking each object via its unique object ID to a formatted and structured .xls, .csv, .txt, or even .pdf file containing corresponding 2D representations of the numbered timber elements. This separation makes it possible to manage and update large volumes of data more efficiently without the need to make changes to the 3D model itself. Each component can be uniquely linked to the relevant data records using object ID. These data records can contain a wide range of information, including material properties, costs, suppliers, maintenance history and other relevant details.
A further advantage of this strategy is that different project parts can access the required information more easily, whether in the context of planning, design or maintenance. For example,

engineers, architects and facility managers can utilise the externally stored data whilst focusing on the graphical 3D model, without being overwhelmed by extensive information.
Furthermore, the use of external files enables easier integration with other software solutions used in the construction and property sectors, such as project management tools or facility management systems. This integration facilitates the exchange of information between the various stakeholders in the construction process and promotes interdisciplinary collaboration. This allows users to continue working either outside the CAD environment or to import the data back into their CAD system — ideally supported directly by the CAD software's development team or by further evolution of the IFC format itself, whether through new fixed categories or enhanced customization options (Fig. 3).

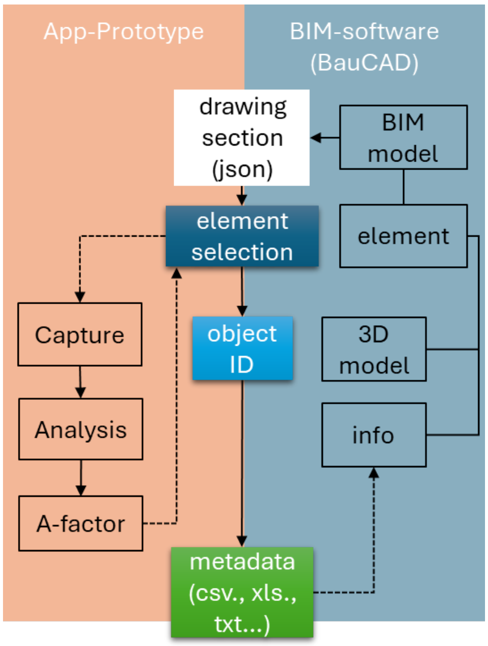

Figure 3. Linking a 3D model element with external structured data.

Another aspect of this strategy is to enhance database management and security. By storing all relevant information externally, backups can be implemented easier, and data integrity and security can be improved. Furthermore, version control systems can be implemented to ensure the traceability of changes throughout the structure's lifecycle.

4. Results

4.1 Smartphone-based app-prototype for wood knots acquisition and analysis

The AI-based method that has been developed by (Pan et al., 2025) is intended for implementation on low-cost mobile devices to enable a user-friendly application for end users (such as craftsmen, restorers and civil engineers) to use on site. The pipeline for app implementation is therefore currently being developed as follows (Fig. 5).
Basically, the app enables image-based RGB capture for automatic knot detection, as well as optional RTI (Reflectance Transformation Imaging) for enhanced visual assessment. The combination of these technologies provides automatic detection of wood knots on aged timber beams, whilst also improving the visual analysis of materials through interactive virtual lighting, derived from RTI data. Users can easily capture timber images, which will be analysed using developed AI-based algorithm to identify wood knottiness factor.
A key feature of the current version is the ability to upload existing plans as PNG or JSON files. This ensures seamless integration into existing planning processes and allows users to view visual representations of timber structures directly within the app. The user interface has been designed to be intuitive and to provide a clear visualisation of the added plans. This not only makes it easier to identify problem areas but also facilitates communication between the various stakeholders involved in timber analysis. In addition, users can interact with the plans and select specific bars.
In addition to benchmarking the model, we also conducted a comparison of the results generated by the AI with measurements obtained through expert manual assessments. The app (Fig. 4) enables users to take photos of wooden beams with their smartphones, which are then automatically interpreted. The result will be an estimated knottiness value, expressed as an A-factor. At the same time, data is transferred to the BauCaD BIM software.

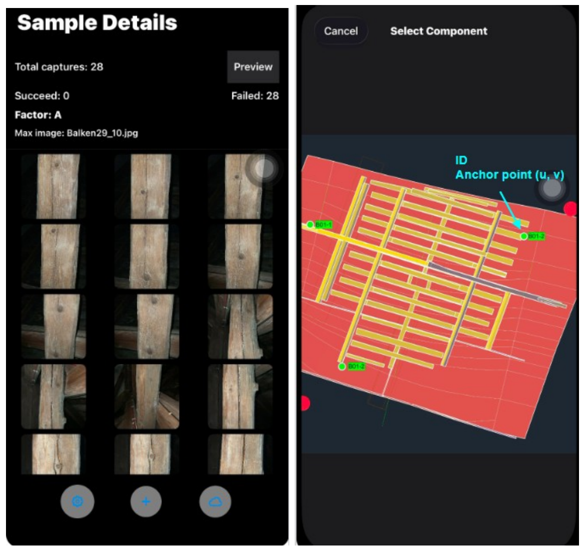

Figure 4. Timber beam selection on json drawing in the app.

4.2 Approach validation

To validate the implemented method, the data was systematically collected by the expert and thoroughly analysed, before being compared with the results from the app. The subject matter expert carried out an on-site visual assessment of the knottiness of old coniferous beams in the roof structure, with the data collected serving as ground truth. This ground truth is used as a reference point for checking and validating the results of the automated, AI-supported knot detection.
To ensure consistency, the evaluation of the iOS-based pipeline (Fig. 6) was performed using the same dataset as the PC-based GPU experiments from the previous research (Pan et al., 2025). The timber elements and associated image sets were processed without modification to ensure a controlled comparison, which can enable performance differences to be attributed solely to the application environment.
Compared to the PC-based results, which yielded a Pearson correlation coefficient of 0.641, the AI-derived factors obtained from the iOS application demonstrate weaker correlations with manual measurements, as evidenced by a Pearson correlation coefficient of 0.458. This reduced correlation suggests that the accuracy of the app's measurements may be affected by various

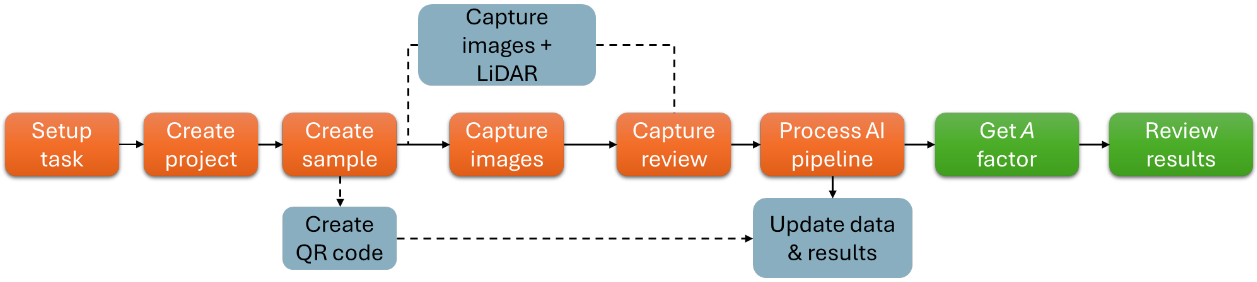

Figure 5. Pipeline for implementing the developed process in the app calculating A-factor (wood knottiness) for particular beam.

factors, such as the limitations of mobile sensor technology, environmental conditions during data collection, or potential differences in user interaction with the application. Moreover, the results from the app exhibit higher variance and several noticeable outliers.

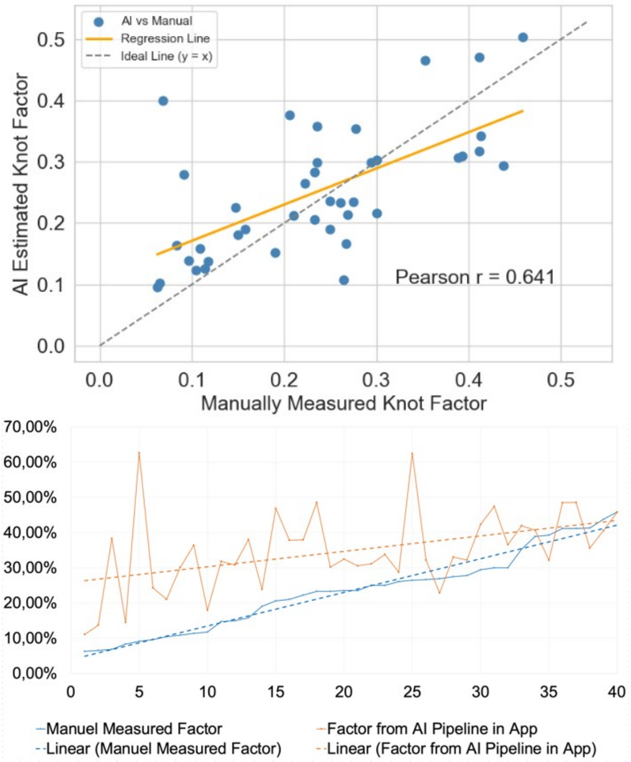

Figure 6. Correlation analysis of knot factors derived from manual measurement and AI-based estimation (top) and processed on iOS (bottom).

The x-axis shows the sample index, sorted in ascending order by the manually measured factor, and the y-axis shows the knot factor as a percentage. The manually measured factor is the reference value derived by experts, defined as the ratio of the shorter edge of the largest visible knot to the corresponding reference dimension. This is calculated using the maximum value across all images per timber sample.

This performance gap is likely caused by differences in the mobile deployment pipeline. The transformation stage on iOS may introduce geometric inaccuracies. These may arise from variations in resolution handling, coordinate precision or polygon simplification. Such inaccuracies directly affect downstream detection and factor estimation. Additionally, converting the model to CoreML, which is specialised for iOS systems, can introduce numerical deviations, such as reduced precision or operator changes. These effects may lead to unstable predictions, particularly for small or ambiguous regions.

Finally, variability is introduced by mobile image acquisition, which can significantly impact the quality of the collected data. Factors such as motion blur, caused by user movement during image capture, automatic exposure adjustments that may not adequately accommodate changing lighting conditions, and viewpoint changes that occur when the camera angle is altered can all further degrade the quality of segmentation and detection processes. These issues may lead to inconsistencies in the data, resulting in less reliable output from the AI models. While the iOS pipeline is practically feasible and offers considerable advantages in terms of accessibility and convenience for end-users, its reduced accuracy underscores the critical need for improvements in several key areas. Specifically, enhancing transformation consistency is essential to ensure that images taken under varying conditions yield comparable results. Additionally, improving model deployment fidelity will help guarantee that the algorithms operate as intended across different devices and scenarios, thereby optimizing performance.

4.3 Data analysis integration in BIM-software

In practice it can be observed that even highly detailed 3D models are often translated into two-dimensional representations once the data is used for analysis, documentation, or communication within project teams. For this reason, it is important that the information contained in the 3D model can also be represented in reliable 2D derivations.

Within BauCaD, the parameters stored in the model can be evaluated automatically and used to generate different types of documentation. These include strength classification plans, damage maps, or element numbering plans. Such documentation can be exported in common formats such as DWG or PDF and can therefore also be used outside a BIM environment. This flexibility ensures that stakeholders, whether they are architects, engineers, or conservation specialists, can access the information they need in a form that is convenient for their specific workflow.

As mentioned before, the interactive capabilities of the app provide an enhanced user experience. By clicking on a selected beam in the app prototype via its unique object ID, users can link that element to a formatted and structured file in .xls, .csv, .txt, or even .pdf format. These files contain corresponding 2D representations of the numbered timber elements, enabling users to easily visualize and analyse the pertinent data associated with each component of the timber structure. This functionality not only streamlines the documentation process but also facilitates efficient communication among project stakeholders, as they can access detailed information relevant to their specific. Figure 7 demonstrates placeholders for illustration of data visualization within the application. In addition to standard timber beam parameters, such as timber species, moisture content, bulk density, modulus of elasticity, etc., the knottiness factor can be displayed. This knottiness factor is an important indicator of the quality and strength of timber. Precise recording and representation of this factor enables a better assessment of the structural integrity of the timber and contributes significantly to the evaluation of load-bearing capacity, what could be useful for building management and life cycle.

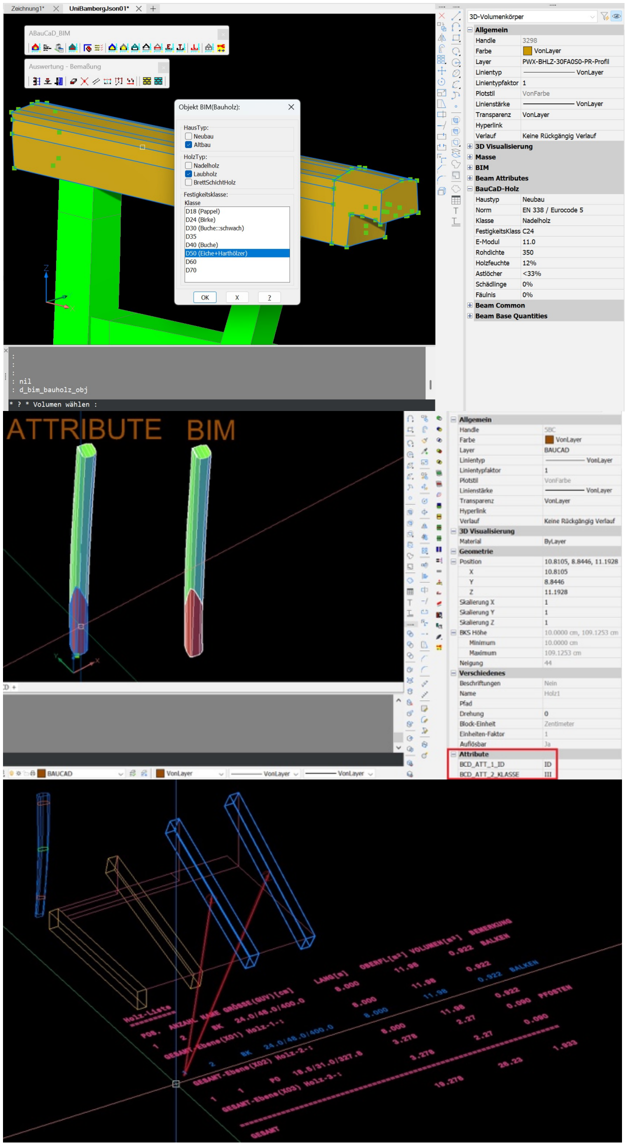

Figure 7. Adding new category for analysis results and its sample visualization of BauCaD model or IFC linkage.

5. Conclusion

In this paper we demonstrate a pipeline of data capture, analysis and transfer from smartphone-based interface prototype analysing automatically wood knottiness factor to BIM.

The integration of advanced AI and machine learning techniques is particularly significant in the context of heritage conservation, where the subtle interplay of visual features associated with degradation poses unique challenges. Traditional methods often rely heavily on subjective human interpretation, which can vary significantly among assessors. In contrast, AI approaches offer the potential for higher consistency and accuracy in defect detection.

Providing precise and reliable analyses in real time, automated structural integrity using wood knottiness estimation enables civil engineers to make informed decisions that enhance both the safety and efficiency of construction projects. Furthermore, this technique reduces the time required for manual assessment and minimises the risk of human error, ultimately leading to more cost-effective and sustainable construction practices.

As part of this research, we will continue to explore the adaptability of the IFC format, as this, like the automation of data acquisition, holds the greatest potential for improving the efficiency of current workflows.

Future developments of open BIM standards may simplify the exchange of such project-specific information. In particular, more flexible mechanisms for defining additional parameters in future IFC versions may significantly improve interoperability between different software systems.

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References

Barontini, A., Alarcon, C., Sousa, H. S., Oliveira, D. V., Masciotta, M. G., & Azenha, M. (2022). Development and Demonstration of an HBIM Framework for the Preventive Conservation of Cultural Heritage. *International Journal of Architectural Heritage*, *16*(10), 1451–1473.

Cheng, Y.-M., Kuo, C.-L., & Mou, C.-C. (2021). Ontology-based HBIM for historic buildings with traditional woodwork in Taiwan. *Journal of Civil Engineering and Management*, *27*(1), 27-44.

Kodytek, P., Bodzas, A., Bilik, P., 2021: A large-scale image dataset of wood surface defects for automated vision-based quality control processes. *F1000Research*, 10, 581.

Kuroczyński, P. and Argasiński, K. (2025). Implementing HBIM for Cultural Heritage Preservation – From Documentation to Sustainable Management, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., X-M-2-2025, 175–184.

Pan, J., Chizhova, M., Ebner, F., Luhmann, T., Ledig, C., Maiwald, F. and Eißing, T. (2025). An End-to-End AI Pipeline for Wood Knot Detection to Enhance Structural Assessment in Historic Timber Structures, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., X-M-2-2025, 267–274.

Previtali, M., Brumana, R., Stanga, C., & Banfi, F. (2020). An Ontology-Based Representation of Vaulted System for HBIM. *Applied Sciences*, *10*(4), 1377.

Santos, D., Sousa, H. S., Cabaleiro, M. and Branco, J. M. (2022). HBIM Application in Historic Timber Structures: A Systematic Review. International Journal of Architectural Heritage, 17(8), 1331–1347.

Wang, X., Wu, C., Zhang, X., and Pan, R. (2025). Bridging Heritage Knowledge and Digital Models: An HBIM Integration Framework, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., X-M-2-2025, 365–372.