De Simone factory, arched openings and brick vaults.

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Modelling for uncertainty in HBIM processes

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Abstract: The application of HBIM for the information management of historical buildings is often hindered by the presence of uncertainty due to limited geometric information and documentation at the time of modelling; controlling and organising this level of uncertainty, in view of future developments, becomes paramount. This paper presents an HBIM workflow to tackle uncertainty by capitalising on parametric modelling and 4D modelling. Parametric modelling is used as a dynamic tool that allows for an easy and quick update of the model when new data become available, while 4D modelling is used for disassembling the building backwards, establishing temporal relationships among building elements and organising them in successive phases, when uncertainty concerns the historical development of building elements and architectural interventions. The workflow was applied to a building of industrial archaeology in southern Italy, the ‘De Simone’ factory, which is abandoned and in a poor state of conservation, but represents a valuable historical testimony due to its rich stratification resulting from significant physical and functional transformations over time. This application shows that structuring the data implementation process to accommodate the available information and its future integration, through the use of parametric and 4D modelling, can be very efficient to support documentation, conservation and enhancement activities on built heritage.

Keywords: HBIM, parametric modelling, 4D modelling, industrial archaeology, built heritage, uncertainty.

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1. Introduction

Building Information Modelling (BIM) is defined as the digital representation of the physical and functional characteristics of a building. It is an information repository to support building design, construction and operation, during the building life cycle (buildingSMARTalliance, 2007; Eastman et al., 2018). HBIM is the application of BIM to historical buildings; the H in the acronym can stand for both Heritage and Historic(al). It is directed to the conservation, management and documentation of built heritage, making data accessible by experts from different disciplines (Pocobelli et al., 2018; Yang et al., 2020).

BIM and HBIM processes are generally based on the same software solutions, the so-called 'BIM authoring tools', which are object-based parametric 3D applications. Starting from a set of fundamental building elements, model objects are defined by parameters and rules that determine both their geometry and non-geometric properties and features, according to the user's control. To provide a coherent 'simulated' representation of building elements and their interaction, this kind of software applications is developed assuming a series of hierarchical relationships and simplifications, deduced from the most common technological systems of the AEC (Architecture, Engineering and Construction) sector: for example, the parallelism of wall surfaces in given directions, the homogeneity of building materials, etc. On the contrary, historical buildings, characterised by different construction systems and complex geometries and properties that have evolved over time, are ill-suited to these logics; thus, there are several issues with adapting BIM use to the modelling of built heritage. Despite these limitations, HBIM presents great potential for the structured collection and organisation of geometric and document information on a historical building, through a 3D interface familiar to those working in the field (Radanovic et al., 2020; Yang et al., 2020).

The workflow for HBIM processes depends on model uses. However, a consolidated HBIM workflow presented in the literature for conservation and documentation (Mammoli et al., 2021; Martinelli et al., 2022) comprises the following steps:

- historical and architectural analysis of the building;
- integrated geometric survey, to obtain the 3D representation of the building (usually point clouds generated by laser scanning and photogrammetry processes);
- general conservation state analysis, including diagnostics, if needed;
- further data collection (pictures, sketches, video recordings, etc.) that can improve the documentation of the building;
- organisation and processing of the analyses' outputs and data collected;
- modelling of the building, generally with a Scan-to-BIM process (a procedure by which a building is modelled using the point-cloud as a 'scaffold' directly in the BIM tool (Radanovic et al., 2020), integrated with the alphanumerical data and documentation collected.

The information represented by an HBIM process generally concerns architectural features, morphology and dimensions of the building's elements, material and construction techniques, historical phases, decay patterns, etc., depending on model uses. Alphanumeric information and documentation can be embedded in the model objects, or integrated in a Common Data Environment (CDE), defined as a structured file repository (generally online) for collecting, organising and disseminating models and documents among the actors involved (ISO 19650-1, 2018). In this case, the connection between model objects and information can be created via links to external files (cartography, pictures, text documents, etc.), stored in the CDE, using parameters which contain their URLs.

Considering the uniqueness and heterogeneity of historical buildings, the workflow described above must be adapted to each particular case, avoiding simplistic theorisations and schematisation. Depending on the required Level of Information Need (EN 17412-1, 2020), the minimum amount of information needed to meet each information requirement should be determined, but no more, as all additional information is considered waste.

Trade-offs between the accuracy of geometric and information data should be explored with the combination of different modelling strategies. For example, geometrically accurate models (e.g., in which the slightest variations in the thickness of the walls are represented), make the use of parametric tools provided by software extremely difficult, greatly limiting their functionality.

Another relevant topic for built heritage is the application of an HBIM process to complex and stratified historical buildings in the presence of uncertainty due to limited information, difficult to obtain during modelling. One issue can be the temporary inaccessibility of the site where the building is located and/or of the building itself. Another difficulty could concern the retrieval of building documentation: historical records, data on the building's consistency, construction techniques, historical phases, etc. A more extreme instance concerns buildings which are partially or totally in ruin: in such cases, if there is also a lack of photographic data and the survey information available is unreliable or incomplete, data integration is difficult. Such issues prevent the application of the workflow described above.

A number of researchers have considered the issue of uncertainty in HBIM processes. The review of Lovell et al. (2023) described various modelling approaches in the face of data unreliability, highlighting the frequency of data voids in HBIM, depending on incomplete documentation and/or inaccessibility during data collection. The former can be mitigated by extending historical-architectural investigations to textual, archival and image-based data and manuals on coeval buildings and local construction techniques; the latter can be overcome with a carefully planned integrated geometric surveys, as carried out by Conti et al. (2022) in applying HBIM on a eighteenth century bridge.

When data gaps are unsolvable, many studies concentrated on the conceptual representation of data reliability, linked to the transparency of information sources, underlining how each building depiction, referring to its current or past phases, is the critical interpretation of a scholar (Cinquepalmi & Tiburcio, 2023; Maiezza, 2019; Scianna et al., 2020). Maiezza et al. (2019) introduced a standard for the evaluation of reliabilities, dependent on the Level of Development (i.e., the standardised framework for defining the amount of detail and accuracy of BIM models, preceding the Level of Information Need). Di Filippo et al. (2022) proposed a statistical treatment of uncertainties related to geometric attributes, differentiating between those deriving from surveys and from parametric modelling. The Level of Reliability (LOR), a global parameter describing the geometric precision and semantic correspondence of HBIM objects (Bianchini & Nicastro, 2018), was also introduced to support the transparency and consistency of information management.

The visualisation of uncertainty in a 3D model, which is paramount for virtual reconstruction as well (Foschi et al., 2024), was tackled by Stefani et al. (2010) using semantisation and model granularity. False colour maps, colour tones or gradient colour codes on 3D geometries are often employed to convey temporal indeterminateness (Adami et al., 2017; Apollonio & Giovannini, 2015; De Luca et al., 2011).

Studies on modelling strategies to practically develop HBIM models in the face of uncertainty are scarce. Doria and Morandotti (2023) described a 3d support system for the historical complex of Bellisomi-Vistarino Palace in Pavia, concentrating on the disused portion of the complex, while Condorelli and Morena (2023) integrated the 3D modelling of a no longer existing phase of the Caltanissetta Centrale Station with photogrammetry from historical images of the building. Brusaporci et al. (2018) proposed a methodology based on three Levels of Development for HBIM objects (from simplified to detailed), depending on the characteristics of the building and the objectives of the study, that can also be applied to representing uncertainty.

A few, critical researches presented HBIM strategies to support the restoration process of buildings seriously damaged by seismic events, such as the Basilica of Collemaggio, hit by the earthquake of L'Aquila in April 2009 (Oreni et al., 2014) and the church of St. Francesco in Arquata del Tronto, struck by an earthquake in 2016 (Banfi et al., 2022). For the Basilica of Collemaggio, Brumana et al. (2018) introduced modelling protocols, called “Grades of Generation”, to describe the geometric accuracy of model objects depending on the geometry detected by the surveys, especially for damaged walls, to obtain a cost-effective modelling process without hindering the quality of information.

These researches are very specific to the modelled building and generally do not tackle the possibility to include new information acquired over time in HBIM processes. However, if the obstacles to information retrieval are temporary, and model uses are not hindered by the lack of data, the development of a specific modelling strategy, that can easily accommodate data integration and update, becomes paramount.

To this end, the current research proposes an HBIM workflow to model for uncertainty, applied to a building with limited but evolving information, by capitalising on the use of parametric modelling and 4D modelling.

1.1 Parametric modelling

Parametric modelling is a modelling process by which the geometry and alphanumeric characteristics of model objects are defined and managed by assigning rules, features and constraints to them (Spallone & Calvano, 2019).

Parameterisation is widely used in BIM and HBIM processes. In the most common BIM tools, these rules are determined by a set of properties of model objects that represent parameters for embedding information or defining relationships with other objects. A parameter, in this case, is expressed by a ‘key-value’ pair, where the key is the name of the parameter itself, which points to its associated value. The value can be constantly modified with data of the same type, producing an immediate update of the model. Insertion and changes can be implemented within the BIM tool for ‘embedded’ values, or externally for 'linked' values. An example of linked value is an externally linked PDF file: by changing its content without changing its name or position, the link between the file and the model is preserved, and the model will display the updated PDF file with the latest changes. Parameters can also be linked to each other, so that the change in the value of one of them produces a specific change in the value of the parameters linked to it.

One of the main applications of parametrisation in BIM is the update of information, both in the design phase, to allow for the exploration of design options, and during operation and maintenance, to accommodate variations during the life cycle of the building. In the representation of built heritage, parametric modelling is often used to build libraries of model objects that represent the modular and rhythmic variability, within the same stylistic approach, of architectural elements.

1.2 4D modelling

The complex data flow of BIM models is represented by the metaphor of BIM 'dimensions', which, beyond the three spatial dimensions, refer to further levels of information (Charef et al., 2018). 4D modelling is defined as the process of combining 3D modelling with time to evaluate time-dependent concerns, such as project phasing, schedules, etc. Through this process, within the most common BIM tools, it is possible to define temporal phases relating to the building life cycle, corresponding with specific points in time when important changes occurred (or are going to occur) to the building construction or operation, or with a more generic temporal indication of the chronological sequence of events affecting the building, depending on model uses. Once the temporal phases are established, model objects are associated with them, indicating, for each object, the phase during which it was or will be built and the phase of demolition, if applicable. 4D modelling allows the management of the entire life cycle of a building, from the design phase to the operation and maintenance phase up to its demolition, creating a model in which the various temporal phases overlap and can be easily visualised both individually and as a whole. In the latter case, the elements belonging to different phases can be distinguished by means of colour filters.

With regard to HBIM, temporal phases are often used to represent the historical development of the building over time, thus indicating the construction phases of building elements, how they were modified, demolished or replaced, and which ones were added in later periods.

1.3 Parametric and 4D modelling to represent uncertainty

Concerning data availability, there are two extreme cases: the case in which no useful data are present and there is no possibility of creating a model that even remotely approximates reality, and the case in which all the data necessary for achieving the model uses are available (pictures, a reliable metric survey, historical data, etc.), thus a model can be created that would not undergo future variations until there is any transformation in the building. Between these two extremes, there is a myriad of cases in which reliable data are flanked by unreliable data with inaccurate or time-varying values. Each model is therefore unique in the way in which, depending on model uses, uncertainty is understood and managed, integrating it with what is certain. There may be a case with no geometric survey available, but with sufficient photos to represent the building conformation, albeit with approximate measurements, or a case where, on the contrary, a lack of photos prevents verifying the reliability of a survey, or cases covered partially by photos and partially by survey data.

In an HBIM process where only limited information on the building is available at the time of modelling, the effectiveness of parametric modelling resides in the possibility of controlling and organising the level of uncertainty caused by the lack of data about the dimensions of building elements, their proportions or their materials, caused by the absence of a reliable geometric survey, historical data, photographic documentation, material composition, etc. In this case, the parametric modelling of building elements, despite an undeniably low LOR, allows for an easy and quick update of the model when new data become available: a flexible modelling strategy, where the mismatch between the building and its representation can be made manifest and therefore controlled. This process should be based on a prior critical assessment: the benefits of parameterisation are not absolute, and it is necessary to choose carefully what building elements, and corresponding model objects, should be parametric, how they should be parameterised, and their Level of Information Need. Parametric modelling thus moves from being a static tool for efficient modelling to a tool to dynamically increase the amount of information in the model and simplify its updates, both from the geometric and alphanumeric information points of view.

Uncertainty may also concern the historical development of building elements and architectural interventions. In this case, 4D modelling can be used for disassembling the building backwards, establishing temporal relationships among building elements and organising them in successive phases. Within HBIM, 4D modelling can therefore be used as a tool not only for representing what is already known, but also for investigating the unknown, exploiting the subdivision into historical phases to find interferences among model objects to gradually formulate a hypothesis of the development of a building over time.

2. Materials and Methods

2.1 Description of the case study

The case study is a building of industrial archaeology, the 'Industria Meridionale Pellami fratelli De Simone & C.s.n.c.' (hereafter named De Simone factory), part of the so-called 'ex-Corradini complex', in the eastern coastal district of San Giovanni a Teduccio in Naples, southern Italy (Figure 1). It is a testimony of the industrial evolution of the area, dating back to the first decades of the 19th century, when the construction of the first Italian railway line Naples-Portici drove the development of a group of factories along the coastal line in the former independent municipality of San Giovanni a Teduccio, which became a relevant industrial centre.

Figure 1 | Localisation and aerial plan of the de Simone factory.

The Corradini Metallurgical Plant, established with French capital in 1872, initially specialised in the processing of copper and brass, later expanding its operations to include the treatment of other metals. Over time, the facility developed along the coastline. Despite changes in ownership and periods of crisis, the plant continued to grow, becoming one of the leading metallurgical industries in the region.

The complex is the result of the aggregation of numerous buildings over more than a century, and it is characterised by a great variety of styles and constructive systems, whose characteristics could trace the origins of the complex to the transition between the 18th and 19th centuries. It hosted numerous functions, from textile and leather production to metallurgy, after the Deluy-Garnier metallurgical factory was implanted here in 1872 and specialised in weapons by the end of the 19th century. Between the two world wars, it reached its highest level of expansion and production. After the bombings of World War II and the enlargement of the railway, production gradually dropped (Betocchi, 1874; Biondi et al., 2008; Del Rio, 1982; Parisi, 1998; Rossi, 1992; Rubino, 1983, 2011).

The De Simone factory is an ancient leather tannery founded by the London-based company Dent Allcroft & Co. Ltd. It is the oldest building in the complex, with a plaque on one of the masonry walls bearing the date 1828. When the company ceased its production, the factory was purchased in 1927 by Industria Meridionale Pellami Fratelli De Simone & Co. snc, one of the most important tanning industries in Naples at the time, specialised in leather processing with traditional tanning methods in underground vats.

This factory, which was active between 1920 and 1927, is housed in a rectangular building within the Corradini complex, covering an area of 5370 square meters, in a single large unit belonging to different historical phases.

Situated at the eastern edge of the Corradini complex, the building can be divided into three parts. The central section appears to be the original core, to which the right wing, used for processing, was later added, followed by the left wing. This central section is divided into two connected parts: a two-storey building and a one-storey building, the latter lighted from above by skylights. The supporting structure consists of tuff masonry walls, with metal beam floors and brick vaults on the first floor, and beams and a reinforced concrete slab with skylights on the second floor. A structural modification is evident, with the removal of partition walls and the installation of sturdy flat beams in paired metal profiles, likely to allow vehicle passage inside the factory. The second section has two levels above ground with a structure in tuff

Figure 2 | De Simone factory, interior.

masonry, cruciform pillars, and masonry arches on the ground floor. It features a central transit area aligned with the main entrance.

The third section, adjacent to the original Corradini complex, has only one floor above ground, except for a small area with an additional level. The main structure is in tuff masonry, with a central area of pillars and reinforced concrete beams. A large space features cast iron columns and trusses, with iron beam floors and vaults.

The complex remained disused for a long time until it was acquired by the municipality of Naples in 1999 and recognised and listed as being of historical-architectural interest. Despite numerous projects for its renovation, its state of conservation appears disastrous, with several buildings partly or completely destroyed, especially on the south side towards the sea, as salts and wind contribute to eroding the tuff of masonry walls. A not-completed asbestos removal, which renders the De Simone factory not accessible, speeded up the degradation process, because coverings were taken off without substitution, thus exposing structures to the elements (Figure 2).

As part of the urban regeneration of the San Giovanni a Teduccio district, the ex-Corradini complex has been involved in a municipality-initiated renovation project. An HBIM process on the De Simone factory was implemented to support the documentation of the building (including historical-architectural analysis, conservation state, spatial and site analysis), the feasibility study and the conceptualisation of design interventions.

Data collection involved bibliographic and cartographic research: historical information on the complex, the De Simone factory and their context is scattered and scarce (Betocchi, 1874; Biondi et al., 2008; Del Rio, 1982; Parisi, 1998; Rossi, 1992; Rubino, 1983, 2011) and it was partially integrated with the analysis of coeval construction systems from architectural manuals (Aveta, 1987; De Sivo et al., 1996; Gangemi, 1991; Penta, 1935; Raia, 2007).

The only graphical documentation available was a lean traditional 2D geometrical survey in CAD, dated 1982, and very few photos: about 28 of the interior, (16 dated May 2005, 12 dated May 2007), not all locatable and covering only a few rooms, a few of the exterior (dated 2018), covering the outer perimeter only along the waterfront, and one of the two main entrances. Inaccessibility due to the presence of asbestos, the risk of collapses and the intricate, almost complete cover of bushes and weeds hindered detailed surveys.

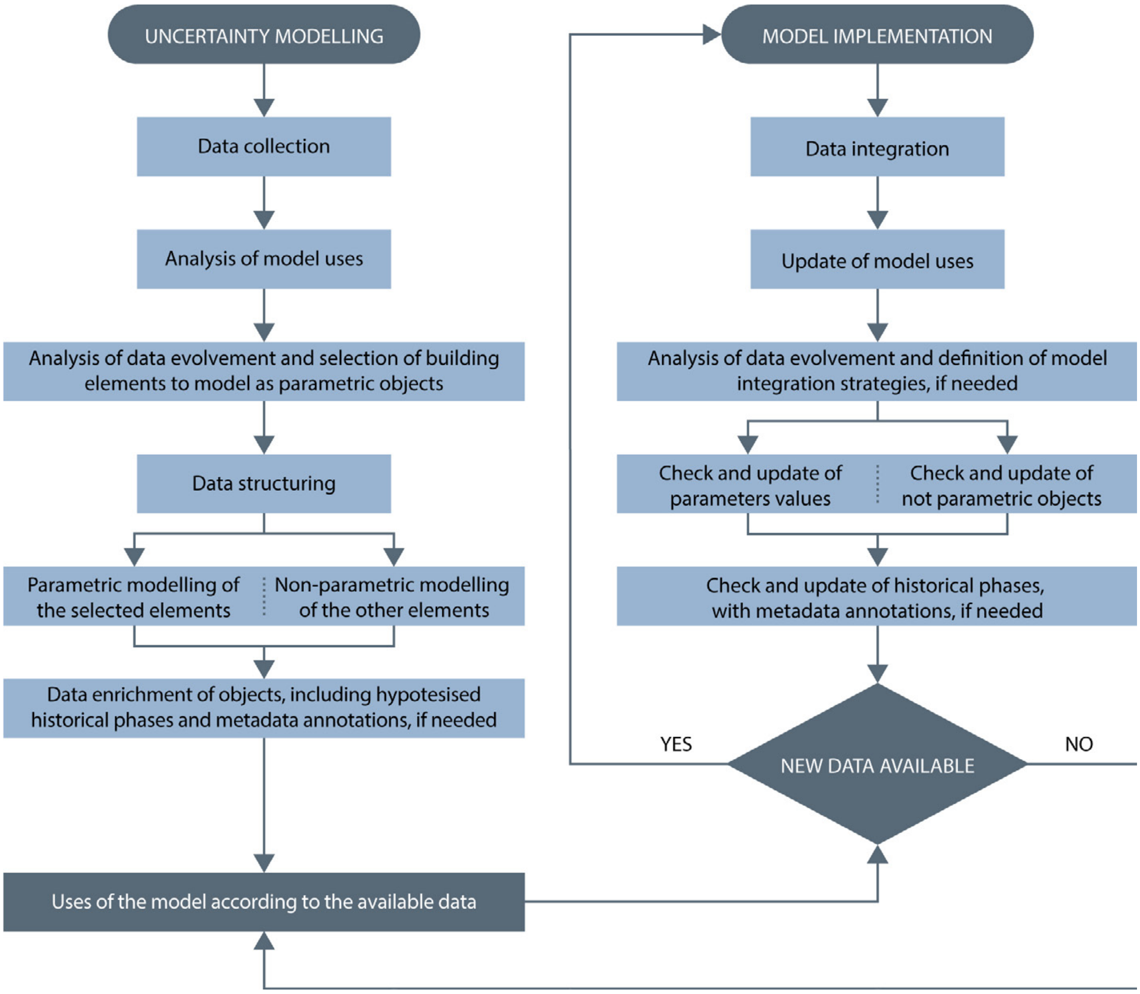


Figure 3 | schematic representation of the proposed workflow.

During HBIM development, aerial photogrammetry of the exterior, partly masked by the dense vegetation, was carried out (June 2020). Safety reasons required an unmanned aerial vehicle (UAV), in this case a drone with built-in camera, used in manual flight mode. The workflow scheme included a detailed flight plan, based on the existing CAD survey and on ortophotos of the area, to ensure the protection of surveyors and instruments and the quality of the images. Both nadir and oblique camera orientations were used to obtain a better representation of building facades. The continuous control of the flight path, provided by the manual flight mode, allowed the surveyors to adapt to the complexity of the area. The photogrammetry was followed by two photographic campaigns (August 2021 and December 2021), which partially integrated the existing information by capitalising on the parametric and 4D modelling workflow proposed.

2.2 Description of the workflow

The workflow applied to the case study is divided into an initial stage, when the HBIM is developed for certain uses despite not having sufficient information to complete it, and an iterative stage of incremental data integration, which is repeated whenever new information useful for the model uses is obtained (Figure 3). Firstly, as much information as possible is collected and, based on the available data, the viability of model uses is analysed. Not only what can be achieved in the future when the missing information is available, but also what can be achieved with the information currently available must be evaluated, since the latter justifies not postponing the modelling until all the data necessary for its completion are obtained.

At the same time, an analysis of the data which will probably change in the future is carried out. This change could be due to intrinsic factors (when data vary over time due to its nature, e.g. the perimeter of a damp patch on a wall) or to extrinsic factors, when the variability depends on the current lack of information. In this case, the corresponding model objects will probably have to be modified when the missing information is obtained: for example, when the height of a column is not available and it is calculated by approximately evaluating its proportions from photos, knowing that, when it will be measured, the height value assigned would be likely modified. Among these changeable objects, the ones to parametrise are selected, by evaluating the cost/benefit ratio in terms of time required to make them parametric (study and application of suitable formulas, tests on constraints, etc.), according to the approximate calculation of how many variations of each object are probable, compared to the time required to rearrange the model without parameterisation, depending on the number of objects with the same type, their complexity, the kind of variations, etc.

All the data collected that will inform the model should be structured to this end: both extrinsic and intrinsic changeability inform a specific model management plan that should simplify future updates of object property values, identifying how to arrange the data, how to name them, how to connect them and to model objects to minimise working effort and the possibility of human error.

After having collected the data and understood how to use them properly, the next step is the coarse modelling of the basic building elements, (generally, the main vertical and horizontal enclosures and partitions). The Level of Information Need for each model object depends on the quantity and quality of current information. If, for example, at the moment of modelling it is not possible to see the construction of floors, they are initially modelled in their most simplified form, e.g., simple flat floors. This step is followed by the parametric modelling of the selected objects and their insertion in the model. Objects are then assigned a hypothetical generic historical phase (phase 00, phase 01, etc.) when it is possible to soundly estimate what comes before and after. Metadata annotations in the model, in the form of comments on each model object, allow one to keep track of what should be checked/validated and the reliability/detail of current modelling. Whenever new useful data are obtained (e.g., more photos, which allow one to better approximate the height of an element, even without having the precise measurement yet), the parameter values involved are corrected, and new parameters are added, if necessary. This is followed by further advancement of the level of accuracy of the model, both in terms of alphanumerical data and historical phases assigned to each object. This iterative integration is performed every time new data are available, with a check on all the values that should be modified according to the updated information.

3. Results

The workflow was applied to the case study of the De Simone factory using the software Revit, which organises model objects into classes called ‘families’. Geometric parametrisation was applied to selected ‘loadable’ families, which are highly customisable external building components, while information parametrisation and 4D modelling were applied to both loadable and ‘system’ families, which represent the main basic building elements, such as walls and roofs.

3.1 Data structuring

After collecting the initially available data on the building, the first step was to systematise these data within a local digital archive, structured into folders and files to be linked to the HBIM model of the building. Data include both raw data and information, with the latter understood as critically processed data.

To link files and folders to the model, relative URLs were employed, to allow for a direct association between them and the model regardless of their absolute location. This approach enhances the portability of the model and data archive, as the connections remain functional even when the archive is moved together with the HBIM model.

The archive, structured as a CDE, was designed not only based on currently available data but also in light of future data additions, facilitating both modifications and the integration of new data.

Data were divided into general information, related to the whole building, and information related to model instances (i.e. single objects). The structure of the archive section containing general information was deliberately loosely defined, as its subfolders depend on the available material, and there is no need to link specific files to individual model objects. Conversely, the structure of the archive section containing information related to instances was more rigidly defined. Specific parameters were linked to each instance, that linked to folders related to degradation, settlement, photos sorted by phase, and LOR.

Information linked to the dimension of time (4D) was stored in folders whose names included the associated phase.

This structure enabled the use of a consistent and effective naming convention to identify model instances, facilitating subsequent updates to the information of each of them.

For instance, it was decided not to tie instances to specific materials or construction types within the archive structure. This ensures that, in the case of human error in material and/or construction type classification, or initial uncertainty leading to hypothetical attributions, subsequent modifications to the material and/or construction type associated with an instance do not require changes to its folder location, thereby preserving all its links to various files in the archive.

3.2 Parametric modelling of the case study

Considering the lack of definite dimensional and proportional data, the elements selected for being parameterised were those that seemed to be present with greater frequency and variations inside the building: their parameterisation would make the whole model easily modifiable if more positive data become accessible.

Although the available geometrical survey had several inconsistencies between plans, elevations and sections, it clearly showed that the openings in the De Simone factory (both doors and windows) are mainly arched, with a wide range of dimensional and proportional variations. This widespread presence of arched openings, as well as slabs made of brick vaults supported by metal joists, led to the identification of the geometric figure of the arc of a circumference as a key parametric element of the model.

Geometrically, an arched opening can be considered to consist of a rectangle, whose height corresponds to the springing line height, surmounted by an arc of a circumference, whose centre is located along the vertical axis of symmetry of the rectangle. The chord's length of the arc coincides with the rectangle's width = w and the span of the arch. The total height of the opening is $h = h_p + h_a$, where h_p is the springing line height and h_a is the sagitta of the arc and the rise of the arch (Figure 4).

Given r as the radius of the arc, $h_a = r$ corresponds to a round arch, while $h_a < r$ to a segmental arch. The case of $h_a > r$ was not considered because it is not present in the case study.

For the parametric modelling of existing arched openings, h, h_p and h_a can be measured directly, while r requires a more complex, indirect measurement and was therefore excluded. Since an arc passes through 3 points, and since the ends of the arc are hinged to the springers, three values are needed to fully define the profile of an arched opening: the span w, the springing line height h_p and the rise h_a.

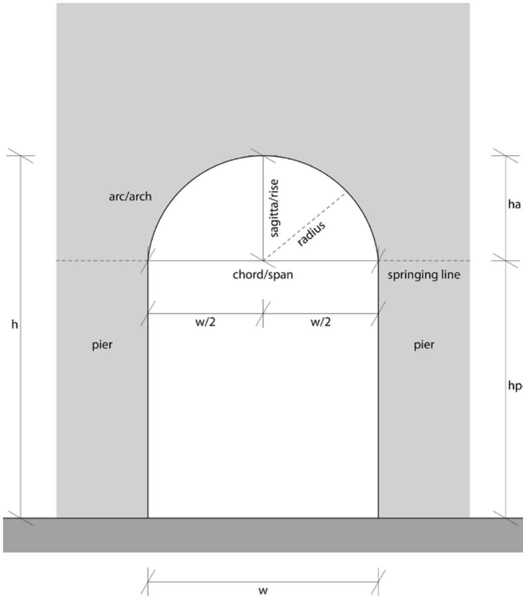


Figure 4 | Elevation of an arched opening, indicating its most relevant parts.

Given that, for modelling purposes, it can be more convenient to establish the total dimensions of an opening (h and w), the three elements can be w, h and h_p or, alternatively, w, h and h_a.

The measurements on the geometric survey and the visual proportional analyses on the available photos showed the presence of arched openings, which, although having different w and/or h values, often seemed to present the same h_p value, or the same proportional ratio $a = h_a / w$. In fact, these are either arched openings inside partially walled up arched openings with the same axis of symmetry, or arched openings arranged in a row along one or more walls.

To account for these geometric relationships, a parametric loadable family of the arched openings was set up, based on the following parameters: h, w, h_p and the value of the ratio $a = h_a / (w/2)$. $w/2$ was used instead of w for convenience, because, in the most favourable case of the round arch, $h_a = w/2 = r$, so $a = h_a / (w/2) = 1$. In this case, moreover, the centre of the arc is on the spring line and each offset of the opening maintains both the same ratio a and the same springing line height h_p.

The variations of the arched openings are within the interval $0 < a \le 1$. The borderline case of $a = 0$ was not considered because a specific parametric model was created for rectangular openings, whose parameters are only h and w.

To simplify and speed up the modelling of arched openings sharing the same h_p and/or a values, within the parametric family developed, the input parameters are: h, w, and a third parameter of choice between h_p or a. The selection of the third parameter is controlled by a boolean (yes/no) parameter called $Inserth_{pValue}$, which governs IF statements.

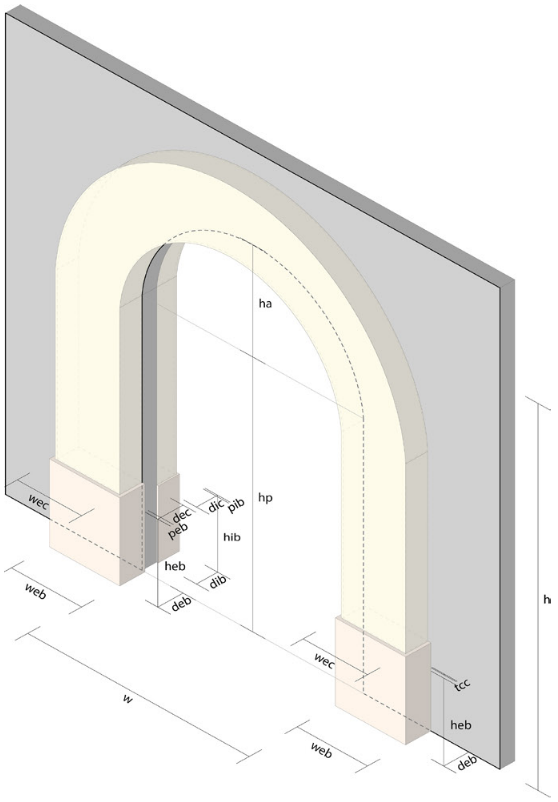
When a single opening is modelled, the choice of h_p or a is indifferent. For a group of arched openings sharing h_p or a values, once the first opening is modelled, to model the others, after inputting the total width w and height h of the opening, there are two cases:

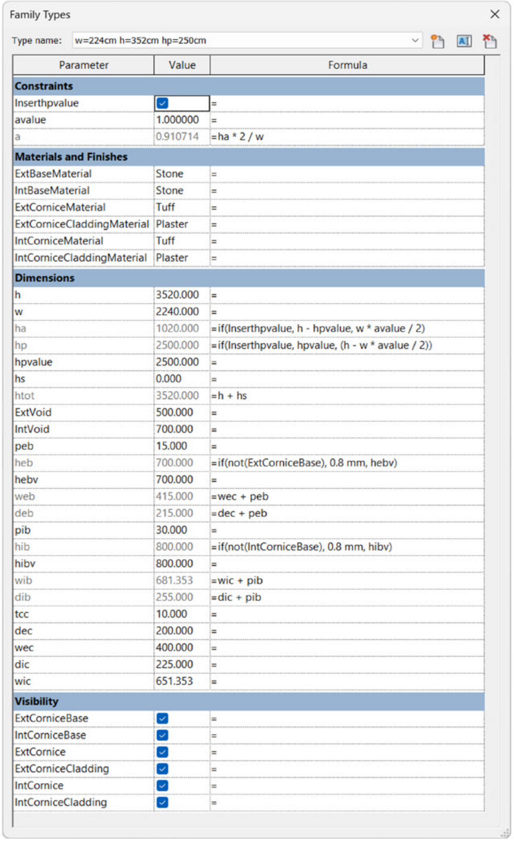
- if the shared value is h_p, the parameter $Inserth_{pValue}$ should be checked and the value h_p of the first opening should be entered; thus, the arc is proportioned automatically, accordingly to reach the total height of the opening h.
- if the shared value is a, the parameter $Inserth_{pValue}$ should be left unchecked and the value of a of the first opening should be entered; thus, the value of h_p is calculated automatically.

The alternative formulas, selected in the two cases by the value of the boolean parameter, are: IF $Inserth_{pValue}$ is checked, h_p value is given by user input (same as h and w), while $a = 2\,(h - h_p) / w$ and $h_a = h - h_p$ are automatically obtained; ELSE, a value is given by user input (same as h and w), while $h_a = w * a / 2$ and $h_p = h - w * a / 2$ are automatically obtained.

Thus, within the software Revit, two intermediate parameters, a_{Value} and h_{pValue}, had to be created for the correct functioning of the formulas. They are the parameters actually associated with the user's inputs, while the dimensions of a and h_p are governed by the corresponding parameters.

Other parameters included the sill height and the presence of a frame on one or both sides of the wall, equal or different; the frame can have a base and can present a material stratification of cladding and structural layer, with the respective material parameters. The actual cut of the wall was also parametrised as a void object, in order to model also arched recesses with customisable parametric depth (Figure 5).





Type name: w=224cm h=352cm hp=250cm

Parameter	Value	Formula
Constraints		
Inserthpvalue	☑	=
avalue	1.000000	=
a	0.910714	=ha * 2 / w
Materials and Finishes		
ExtBaseMaterial	Stone	=
IntBaseMaterial	Stone	=
ExtCorniceMaterial	Tuff	=
ExtCorniceCladdingMaterial	Plaster	=
IntCorniceMaterial	Tuff	=
IntCorniceCladdingMaterial	Plaster	=
Dimensions		
h	3520.000	=
w	2240.000	=
ha	1020.000	=if(Inserthpvalue, h - hpvalue, w * avalue / 2)
hp	2500.000	=if(Inserthpvalue, hpvalue, (h - w * avalue / 2))
hpvalue	2500.000	=
hs	0.000	=
htot	3520.000	=h + hs
ExtVoid	500.000	=
IntVoid	700.000	=
peb	15.000	=
heb	700.000	=if(not(ExtCorniceBase), 0.8 mm, hebv)
hebv	700.000	=
web	415.000	=wec + peb
deb	215.000	=dec + peb
pib	30.000	=
hib	800.000	=if(not(IntCorniceBase), 0.8 mm, hibv)
hibv	800.000	=
wib	681.353	=wic + pib
dib	255.000	=dic + pib
tcc	10.000	=
dec	200.000	=
wec	400.000	=
dic	225.000	=
wic	651.353	=
Visibility		
ExtCorniceBase	☑	=
IntCorniceBase	☑	=
ExtCornice	☑	=
ExtCorniceCladding	☑	=
IntCornice	☑	=
IntCorniceCladding	☑	=

Figure 5 | Loadable family of the arched opening in Revit, highlighting the parameters used for modelling.

Another example of parameterisation based on the arc of a circumference is the loadable profile family developed for the brick vaults pertaining to the Revit category of floors, whose dimensions (arcs) in the transversal section are constant for each floor, as well as the dimensions and spacing of the supporting joists.

To model a floor with brick vaults, it is first necessary to draw the profile of the individual vault within a profile family, also indicating the space that will be occupied on its sides by the joists on which it rests. The profile family is a loadable family that contains a 2D shape that can be loaded into a project and applied to certain building elements, like floors. The loadable brick vault profile family is then loaded into the system family ‘floor’, creating the ‘floor with brick vaults’ type.

The profile of the transversal section of the vault was parametrised as an arc of a circumference.

Assuming that the supporting joists have a constant width and height for each floor, corresponding to a room, that the rooms can be considered rectangular with variable dimensions and that the rise of the arc of the vaults *h’* is proportional to the height of the joists, the variable elements of the vault are *h’* and its width *w’*, corresponding to the sagitta and the chord of the arc respectively. *h’* can be measured by reducing the height of the joist by a certain amount taking into account the dimensions of the vault’s bricks; *w’* depends on the spacing of the joists = *p* and on the joists’ width = *b*, according to the formula: $p = w' + 2(b/2) = w' + b$ which simplifies to $w' = p - b$.

In the parametric family, inserted the parameters *h’*, *p* and *b* with user inputs, *w’* and the radius *r* of the circumference that originates the arc are automatically obtained, and the profile shape is parametrically generated. The following formula, based on the properties of right triangles, returns the radius = *r*:

$$r = [(h'^2) + (w'/2)^2] / (2h') \tag{1}$$

which derives from:

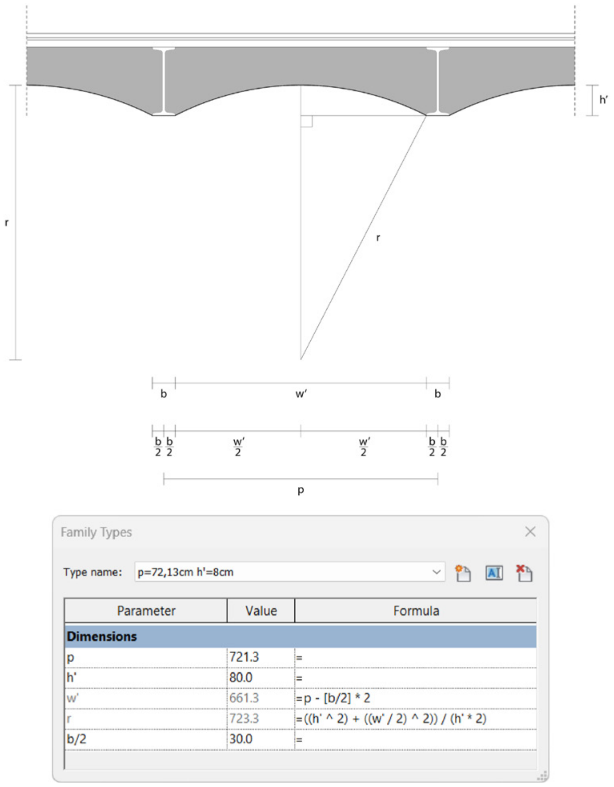
$$h' = r - \sqrt{r^2 - \frac{w'^2}{4}} \rightarrow r^2 - \frac{w'^2}{4} = (r - h')^2 \rightarrow$$

$$\rightarrow r^2 = \frac{w'^2}{4} + r^2 - 2rh' + h'^2 \rightarrow$$

$$\rightarrow r = \frac{w'^2}{8h'} + \frac{h'}{2} = \frac{\left(\frac{w'}{2}\right)^2}{2h'} + \frac{h'^2}{2h'} =$$

$$= \frac{\left(\frac{w'}{2}\right)^2 + h'^2}{2h'}$$

as shown in Figure 6.



Type name: p=72,13cm h'=8cm

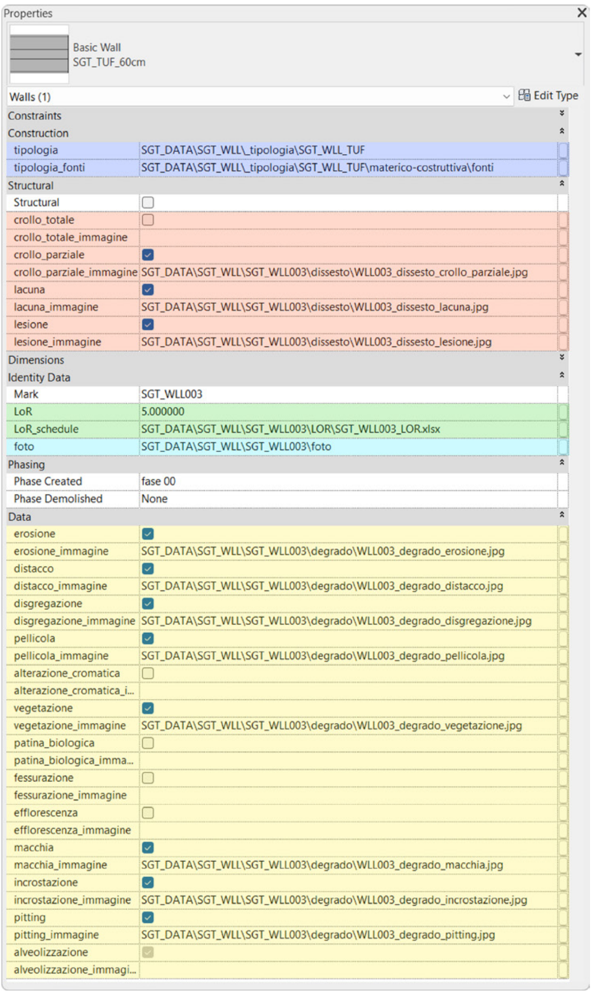
Parameter	Value	Formula
Dimensions		
p	721.3	=
h'	80.0	=
w'	661.3	=p - [b/2] * 2
r	723.3	=((h' ^ 2) + ((w' / 2) ^ 2)) / (h' * 2)
b/2	30.0	=

Figure 6 | Loadable family of the arched profile of the brick vaults, highlighting the parameters used for modelling.

After the photographic campaigns of August and December 2021, which allowed us to analyse in detail the rooms of the ground floor and the external facades of the building, it was possible to test the efficacy of the parametrisation previously carried out.

Regarding the arched openings, thanks to the new photos and few measurements acquired, their proportions and dimensions were better approximated to reality in each room of the ground floor, easily and effectively, by simply modifying the values of *w*, *h* and, alternatively, depending on the case, the value of h_p or *a*.

Regarding the brick vaults of floors, the new photos enabled us to count the number of vaults in each room. Thus, it was possible to note the changes in the spacing of the joists *p* in each room, and therefore in the arc’s width *w’*. Analysing the construction system of the floors together with the photos, it was assumed that the height of the vault is constant and equal to *h’* in each room (save variations due to decay and damages or executive errors). In this case, by varying the value of *w’* while *h’* remained constant, the radius *r* varied accordingly.



Constraints	
Construction	
tipologia	SGT_DATA\SGT_WLL_tipologia\SGT_WLL_TUF
tipologia_fonti	SGT_DATA\SGT_WLL_tipologia\SGT_WLL_TUF\materico-costruttiva\fonti
Structural	
Structural	☐
crollo_totale	☐
crollo_totale_immagine	
crollo_parziale	☑
crollo_parziale_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\dissesto\WLL003_dissesto_crollo_parziale.jpg
lacuna	☑
lacuna_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\dissesto\WLL003_dissesto_lacuna.jpg
lesione	☑
lesione_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\dissesto\WLL003_dissesto_lesione.jpg
Dimensions	
Identity Data	
Mark	SGT_WLL003
LoR	5.000000
LoR_schedule	SGT_DATA\SGT_WLL\SGT_WLL003\LOR\SGT_WLL003_LOR.xlsx
foto	SGT_DATA\SGT_WLL\SGT_WLL003\foto
Phasing	
Phase Created	fase 00
Phase Demolished	None
Data	
erosione	☑
erosione_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\degrado\WLL003_degrado_erosione.jpg
distacco	☑
distacco_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\degrado\WLL003_degrado_distacco.jpg
disgregazione	☑
disgregazione_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\degrado\WLL003_degrado_disgregazione.jpg
pellicola	☑
pellicola_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\degrado\WLL003_degrado_pellicola.jpg
alterazione_cromatica	☐
alterazione_cromatica_i...	
vegetazione	☑
vegetazione_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\degrado\WLL003_degrado_vegetazione.jpg
patina_biologica	☐
patina_biologica_imma...	
fessurazione	☐
fessurazione_immagine	
efflorescenza	☐
efflorescenza_immagine	
macchia	☑
macchia_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\degrado\WLL003_degrado_macchia.jpg
incrostazione	☑
incrostazione_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\degrado\WLL003_degrado_incrostazione.jpg
pitting	☑
pitting_immagine	SGT_DATA\SGT_WLL\SGT_WLL003\degrado\WLL003_degrado_pitting.jpg
alveolizzazione	☑
alveolizzazione_immagi...	

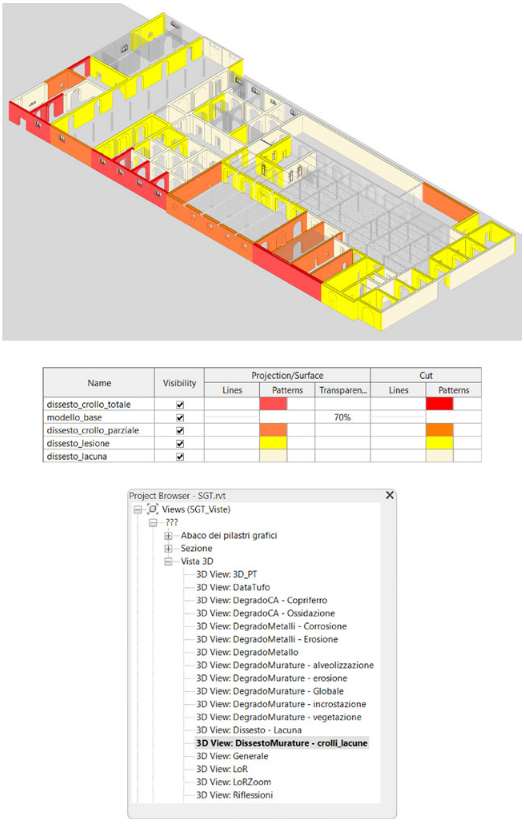
Figure 7 | Integration of properties to represent the non-geometric attributes of model objects, e.g. LOR, information on constructive systems, pictures of the tipologies of decays and damages.

Parameterisation was used not only for geometric information but also for representing and archiving other types of data available on the building, e.g. data related to materials, decay patterns and structural damages, which became visible and could be hypothesised with sufficient accuracy from the new photos. Again, modelling methods and Level of Information Need were critically chosen and strictly linked to the specific case study, to make this information easily updateable, according to a hypotetical increase in knowledge or intrinsic variations in the data available.

Not having metric data to precisely map the various types of decay and damages, they were reported directly on the photos.

Therefore, for each type of decay and damage, a boolean parameter *DecayDamageType* and a URL parameter *DecayDamageType_image* were created for every object of the model as instance parameters (that is, modifiable for every single object). The *DecayDamageType* parameter of an object must be checked if that object is subject to that specific type of damage.

In the *DecayDamageType_image* parameter, a relative URL of a file or a folder can be inserted, to link each object to photos and/or documents that show and describe the decay and damage, which open automatically by clicking on the URL in the properties window of the selected object (Figure 7).



Name	Visibility	Projection/Surface			Cut	
		Lines	Patterns	Transparen...	Lines	Patterns
dissesto_crollo_totale	☑		🟥			🟥
modello_base	☑			70%		
dissesto_crollo_parziale	☑		🟧			🟧
dissesto_lesione	☑		🟨			🟨
dissesto_lacuna	☑		⬜			⬜

```
Project Browser - SGT.rvt
⊟ Views (SGT_Viste)
  ⊟ ???
    ⊞ Abaco dei pilastri grafici
    ⊞ Sezione
    ⊟ Vista 3D
        3D View: 3D_PT
        3D View: DataTufo
        3D View: DegradoCA - Copriferro
        3D View: DegradoCA - Ossidazione
        3D View: DegradoMetalli - Corrosione
        3D View: DegradoMetalli - Erosione
        3D View: DegradoMetallo
        3D View: DegradoMurature - alveolizzazione
        3D View: DegradoMurature - erosione
        3D View: DegradoMurature - Globale
        3D View: DegradoMurature - incrostazione
        3D View: DegradoMurature - vegetazione
        3D View: Dissesto - Lacuna
        3D View: DissestoMurature - crolli_lacune
        3D View: Generale
        3D View: LoR
        3D View: LoRZoom
        3D View: Riflessioni
```

Figure 8 | 3D view with graphic visibility filters highlighting damages.

The boolean parameters were also used to create 3D views in which all the objects subject to each decay and damage are highlighted in colour, thanks to graphic visibility filters, with automatic updates of the views in case of modification of the related parameters (Figure 8).

3.3 4D modelling of the case study

Due to the lack of historical data available, starting from the current situation, the goal of 4D modelling was to postulate how the building had changed over time and deduce its most probable initial conformation.

Signs of transformations of the openings over time have been already visible in the first available photos of the case study, allowing for a sound hypothesis of their development.

In particular, traces of subsequent shrinkages of the arched openings, of their cut or, in some cases, of their complete closure, were visible, probably, due to the changes in the intended use of rooms. Therefore, the transformations in the openings were studied from a constructive point of view, hypothesising which interventions were coeval, which were certainly subsequent and which were certainly previous, in order to organise and then model them into their corresponding historical phases within the BIM software application Revit.

Given a wall *A* which, in '*phase 00*', presents an arched opening *a* with height *h* and width *w*, a question to solve within the software was to show that, in '*phase 01*,' the opening was reduced to a height $h' < h$ and a width $w' < w$. The procedure used was the following: defining the time phase; creating a wall *A* with an arched opening *a* in '*phase 00*', then a wall *B* in '*phase 01*' which closes the opening *a*; inserting an arched opening *b* inside the wall *B*.

By inserting an arched opening *a* into wall *A*, Revit automatically cuts the wall to define the reciprocal behaviour of the two contsructive elements. If this opening is then walled up by wall *B*, it automatically reaches the height of the opening, but does not automatically follow a non-rectangular profile, partially overlapping with wall *A*. At present, to solve this problem, the profile of wall *B* must be manually modified, making it coincide with the profile of the opening *a*: this is a critical issue that limits the automatisms of parameterisation. With regard to arched openings with more than one subsequent shrinkage, this procedure must be repeated for each historical phase in which there is a shrinkage, starting from the initial phase of the original opening, up to its current situation.

4D modelling also made it possible to indicate, in the HBIM model, the intersection and/or cut of the openings by other elements. For example, if photos show a walled-up arched opening crossed transversely by a partition, the following sequence of transformations can be hypothesised: a wall with an arched opening built in '*phase 00*', the closure of the opening in '*phase 01*', the construction of the transversal partition in '*phase 02*'. If there is a trace of an arch cut by a rectangular opening, the following sequence of transformations can be hypothesised: a wall with an arched opening built in '*phase 00*', the closure of the opening in '*phase 01*', the creation of a rectangular opening in '*phase 02*'.

By cross-referencing the various temporal relationships of the specific objects that were identified from the photos and represented in the HBIM model, we deduced a global hypothesis of the transformations of the main elements (openings, walls and floors), hence of the rooms, and hence of the De Simone factory in its entirety, based on the most plausible construction sequence of the identified interventions.

This hypothesis, and its representation in the HBIM model, could also be easily updated if new historical data become available, since it will be sufficient to update the historical phase of the model objects as a parameter.

4. Discussion

The results obtained from de Simone factory allowed us to identify benefits and criticalities of the proposed methodology of modelling for uncertainty in HBIM. For instance, it highlighted the essentiality of a correct initial structuring of the available data, designed taking into account possible future updates and/or integrations that can be subsequently updated. The flexibility of the process allowed for corrections during the modelling phase, but planning data management in advance, starting from data analysis, remains paramount.

It is also recommended to concurrently perform a breakdown structure of the building into elements to model and assess which of them can benefit the most from parametric modelling in the case of model updates. More specifically, the advantages of parametric modelling have been evident in the case of objects that are frequent, have a defined typology yet present many dimensional and/or proportional variations, but whose modelling depends on simple geometric formulas, such as arched openings. In the case of infrequent, complex objects, consisting of many different parts and/or requiring complicated geometric formulae, such as the non-standard trusses of the De Simone factory, the cost/benefit ratio, in terms of the time needed for modifications caused by dimensional updates, pushes towards non-parametric modelling. It should also be emphasised that parametric modelling, due to its higher difficulty compared to non-parametric modelling, if not carefully handled by expert modellers may also lead to bugs in the modelling software used, all the more frequent the greater the complexity of the object to model.

Regarding 4D modelling, it should be emphasised how significant it was in allowing us to understand the development of the De Simone factory over time. The possibility, offered by several BIM modelling tools, to represent the construction phases of a new building proved easily adaptable also to describe the historical phases of individual model objects. By temporally ordering them on the basis of visual evidence, it was possible to derive the chronology of the macro structures constituting the complex, up to a general hypothesis of the original conformation of the building. 4D modelling thus proved to be not only a documentation tool, but as important a knowledge process as parametric modelling.

In fact, in the face of uncertainty, the modelling phase in itself is a knowledge phase of what is being modelled: visual representation in the form of drawing has constantly provided a very powerful tool for in-depth analysis of form and its genesis. In the case of information modelling, this concept is also extended to the non-geometrical data integrated into HBIM: their structuring and management, in connection with the geometrical model, increases their investigation potential, and subsequently the degree of knowledge they can produce, both for individual objects than for the whole building they constitute.

5. Conclusions

This study presented an HBIM workflow able to tackle the uncertainty due to limited geometric and semantic information at the time of modelling, by means of parametric and 4D modelling. The workflow was applied to the industrial archaeology building De Simone factory, in southern Italy, starting with the collection and structuring of initially available data, which informed the modelling process. Among the most interesting elements modelled parametrically there were arched openings and vaulted ceilings, whose modular geometry and local variations rendered this modelling strategy especially effective. Alphanumeric attributes were also added to each object in the model to associate information such as decay patterns and damage.

Parametric modelling has been integrated with 4D modelling: each object in the model is associated with a specific construction phase, related to the chronological development of building elements. This allows to hypothesise the changes occurred to the De Simone factory and to visualise, within the model, the extension of the building at these different stages.

This process highlighted the relevance and consequence of uncertainty in the case of built heritage, especially vernacular/not monumental architecture, which is generally not properly documented, but could be significantly stratified due to notable physical and functional transformations occurred over time, as well as buildings in poor state of conservation or abandoned. Therefore, structuring the data implementation process to accommodate the information available at the time of modelling, but also its future integration, can be very efficient.

For morphologically complex buildings such as the De Simone factory, the HBIM modelling process, encompassing information modelling, parametric modelling and 4D modelling, leads to a considerable increase in knowledge even when little data is initially available, because their systematisation, both geometric and non-geometric, rendered easily updatable, as if the model itself were a construction site in continuous evolution, leads to discoveries that would be difficult without. This methodology allows a careful re-structuring of what is currently available, with an eye to what might happen in the future, and is aimed at obtaining practical knowledge for the management, conservation and enhancement of the given historical building.

The De Simone factory also shows how the proposed workflow can be effectively employed in the cases where, even if uncertainty is not critical, it is anticipated that the building to model will undergo transformations and evolutions; thus, information should be organised in a way that makes subsequent updates easy.

Parametric and 4D modelling emerge as powerful tools to complement information management to support documentation, conservation and enhancement activities on built heritage.

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