Building aggregate of "La Giudea", Santo Stefano di Sessanio (AQ): view of the interior courtyard.

VITRUVIO 8 | Special Issue 1 (2023)
International Journal of Architecture Technology and Sustainability

On the interoperability performance of HBIM models for structural conservation and upgrading of building aggregates in the Italian minor centres

Adriana Marra[1], Giovanni Fabbrocino[2,3], and Ilaria Trizio[3]

[1] Department of Civil, Construction-Architectural and Environmental Eng., University of L'Aquila
[2] Department of Biosciences and Territory, University of Molise
[3] Institute for Construction Technologies, Italian National Research Council.

Abstract: The article deals with the definition and evaluation of a workflow to demonstrate that the parametric model of a historic building with a high level of digital maturity can be configured as a tool that fosters collaboration between the various professionals involved in the recovery and rehabilitation process of historic buildings. It also represents the starting point for developing structural models for quantitative analyses. The implementation of HBIM to the building aggregate called "La Giudea" in Santo Stefano di Sessanio (AQ), an artefact that is particularly representative of the historical building heritage of the small medieval village in the Abruzzo Inner Areas, has provided a model for managing the information deriving from the knowledge process. The model delivers to the use of the state of conservation, and it represents the base for the structural analysis of the asset and the identification of the measure and interventions for its preservation. The parametric model was developed in the design of strengthening and restoration works requiring interactions between digital environments. In such a framework, an investigation aimed at evaluating the interoperability of the digital model and particularly the vertical interoperability between different software packages has been explored.

Keywords: interoperability, architectural heritage, digital survey, HBIM, structural model.

Cite as: Marra, A., Fabbrocino, G., and Trizio, I. 2023. 'On the interoperability performance of HBIM models for structural conservation and upgrading of building aggregates in the Italian minor centres'. *VITRUVIO - International Journal of Architectural Technology and Sustainability*, *8*(special issue), pp. 140-151. https://doi.org/10.4995/vitruvio-ijats.2023.18856

1. Introduction

The topic of HBIM (Historical Building Information Modeling) has found growing importance in recent years in the field of issues related to the representation of historical buildings. HBIM derives directly from the Building Information Modelling (BIM) paradigm and has demonstrated great potential for the digital documentation process of historic buildings from the beginning. Parametric modelling of historic buildings was first oriented to support restoration projects (Continenza *et al.*, 2016; Oreni *et al.*, 2017; Fiorani, 2017), representing a useful tool for the management of reconstruction in the areas of our territory recently affected by earthquakes (Trizio *et al.*, 2017; Brumana *et al.*, 2018; Trizio *et al.*, 2019; Brumana *et al.*, 2020), despite some limitations that have often led to a critical review (Della Torre, 2017). The methodology has also been tested in the field of historical heritage diagnosis, moving towards Diagnosis-Aided Historic Building Information Modeling and Management (Bruno *et al.*, 2018). Subsequently, some application has been directed towards monitoring, leading to digital twins (Marra *et al.*, 2021) that are models to be developed to deal with automated collection and to enable the constant monitoring of potential risks using automated procedures.

The next step saw the in-depth use of parametric models generated using HBIM to perform structural evaluations of existing artefacts (Pepe *et al.*, 2020; Abbate *et al.*, 2022). The potential of parametric modelling has also been extended to historical city centres through the use of City Information Modelling (CIM) to define a workflow that quickly enables the acquisition, modelling and structural analysis of urban aggregates (Saccucci and Pelliccio, 2018; La Russa *et al.*, 2022).

This is the background of the present paper, whose objective is to deliver some reflections on the points of strength and weakness of a comprehensive process of design covering the architectural, engineering and preservation aspects in the digital environment offered by technical software packages. The attention is particularly focussed on the villages of the Abruzzo Apennine, being this area impacted by strong earthquakes in the last decades and an effort in reconstructing and recovering existing buildings is still under development. The problem is analysed from the perspective of the designer or the design team engaged in the execution of different and complex activities spanning from the survey, the analysis of materials and damage analysis, the evaluation of current structural performance and the design of restoration and strengthening works.

Therefore, attention in the following is focused on the operational process and the integration of hardware and software tools generally available to designers and disregards the in-depth examination of specific structural analysis and design problems. In other words, the contribution intends to highlight the need for training and continuous professional updating of operators about the different and multiple software tools and platforms available. At the same time, it investigates the interoperability that tools and platforms must offer to facilitate the design phases and, above all, to open up concrete prospects for the use of digital environments in management and maintenance.

2. Peculiarities of an architectural complex in a medieval settlement

Typical examples of architectural complexes located in the minor centres of the Abruzzo Apennines can be found in the municipality of Santo Stefano di Sessanio, in the province of L'Aquila. It is a small village of medieval origin still affected by the reconstruction activities after the 2009 earthquake that affected a large part of the L'Aquila area.

Santo Stefano di Sessanio is one of the best-known municipalities on the southern slope of the Gran Sasso, and, in the past, it was the centre of intense cultural exchanges with even very distant territories due to its location along the *Via degli Abruzzi* (Magistri, 2013). Indeed, the *Via degli Abruzzi*, a route for the wool trade, connected Naples and Florence and passed through Abruzzi and, particularly between the 13th and 15th centuries, ensured considerable cultural and economic activity for this area. The village, which was part of the Baronia of Carapelle, reached its maximum development under Medici rule, which lasted about 150 years and began in 1579 following the transfer of the Barony to Francesco de' Medici (Bartolomucci and Donatelli, 2012).

Santo Stefano di Sessanio is located on the top of a hill at 1251 metres above sea level and is characterised by an elliptical-shaped central settlement that follows the orography of the hill on which it stands and on top of which stood the Medicean tower, which collapsed during the 2009 earthquake, recently rebuilt and returned to the local community in October 2021. The urban layout follows the morphology of the hill, with streets running parallel to the contour lines and connected by transversal stairways along which the terraced buildings are placed. The recurring building typology, as in many other centres of the area, is that of houses against the mountainside, which develop in height and are characterised by downhill facades reaching three or more storeys (Fig. 1). Access to such terraced houses is generally upstream, inside the village, thus emphasising the defensive character of the settlement (Bartolomucci and Donatelli, 2012). The building fabric is characterised by fortress-houses, tower houses, terraced

Figure 1 | Top and panoramic view of the village of Santo Stefano di Sessanio.

houses and covered passageways (Fig. 2) created by the elevations resulting from the merging of building blocks during the expansion of the settlement within the walls and determined by the saturation of the available lots (Bartolomucci *et al.*, 2012).

The use of vaulted elements in the expansion phase of the village arose to satisfy specific functional requirements such as protection of the external passages from snow, anti-seismic protection between the parallel building blocks and exploitation of the upper spaces to obtain additional inhabited floors (Marson *et al.*, 2013). In the following, attention is focused on a building aggregate, subject to perimeter delineation during the 2012 Reconstruction Plan (PdR) drafting, located along *Via della Torre*, near *Piazza della Guidea*. It has the characteristics of a fortress-house, being located along the outer perimeter of the village itself and is adjacent to one of the main historical gates, *Porta Leone*. The building, closed around a small internal courtyard (4.5 m long and 2.3 m wide) accessed through a round-arched stone portal, is characterised by an entrance to the first floor through an external masonry staircase (*profferlo*) with a pointed arch. The building aggregate presents an irregular shape, both in plan and elevation, with several backward and protruding volumes and a height that ranges from 16 m on the outer façade to 6.5 m on the inner façade.

Figure 2 | Recurring construction peculiarities in the buildings of the village.

The place names that characterise the building's surroundings, locality and *Via della Guidea* suggest that, in the past, it may have had relations with some Jewish community, as in the case of similar villages in the same area that have preserved traces left by the presence of ghettos within them.

3. Material and methods

An extensive knowledge of the artefact must be achieved through shared multidisciplinary approaches (MIBACT, 2011) to identify the strategies to be implemented for safety and conservation of the historical heritage. The knowledge phase includes the acquisition of heterogeneous data, both qualitative and quantitative, which are relevant for the subsequent analysis phases. Both processes can benefit from the advantages offered, in terms of solutions and procedures, by digital technologies through the implementation of virtual replicas of the artefact under investigation (Messaoudi *et al.*, 2018; Bronzino *et al.*, 2019).

In this context, HBIM (Historical Building Information Modelling) models represent the most effective solution to collect and manage the multitude of information arising from the knowledge process (Continenza *et al.*, 2016; Lanzara *et al.*, 2021).

The possibilities offered by HBIM in the field of cultural heritage are numerous. While these informative models guarantee and improve access to the data acquired in the survey processes, they also simplify the quantitative analyses useful for identifying conservation and management strategies for the historic built (Doria *et al.*, 2018; Currà *et al.*, 2021), thanks to the interoperability between different software guaranteed by the open format IFC (Industry Foundation Classes) (BuildingSMART, 2022; Gerbino *et al.*, 2021). Based on these assumptions, a detailed digital model of the structural aggregate "La Giudea" was implemented in a parametric environment, in order to manage the information resulting from the knowledge process, document the current state, analyse the structural behaviour and identify the actions to be implemented from the conservation perspective. The operative workflow adopted to develop the HBIM model, as already experimented with historical infrastructures (Trizio *et al.*, 2021a), is characterised by two distinct but not disjointed phases and is aligned with the multidisciplinary approach foreseen by Italian regulations (MIBACT, 2011; NTA, 2018; Circular 7, 2019).

In the first phase, information regarding the history, evolution and geometric-formal characteristics of the aggregate was acquired, which was then appropriately digitised to improve its accessibility.

During the data acquisition phase, an instrumental survey of the aggregate was carried out to obtain detailed data regarding the geometric and dimensional characteristics of the artefact, as well as those relating to the cracking and deformation framework of the structures. The survey of the aggregate was carried out in three distinct phases, recurring to different indirect survey methods and technologies identified according to the objective to be achieved and the desired level of detail (Fig. 3).

In the first phase, the interior spaces were acquired through Leica's Disto 3D, which returned the points in 2D and 3D vector mode in real time, offering immediate visual feedback. In the next phase, the outdoors was scanned through a mobile mapping system (MMS). Specifically, three scans were carried out with the mobile laser scanner ZEB Horizon by Geoslam through closed loops lasting an average of 10 minutes.

This tool, thanks to SLAM (Simultaneous Localization And Mapping) technology, allows the acquisition of good quality 3D data, i.e. with an accuracy of 1-3 cm, despite the reduced acquisition time.

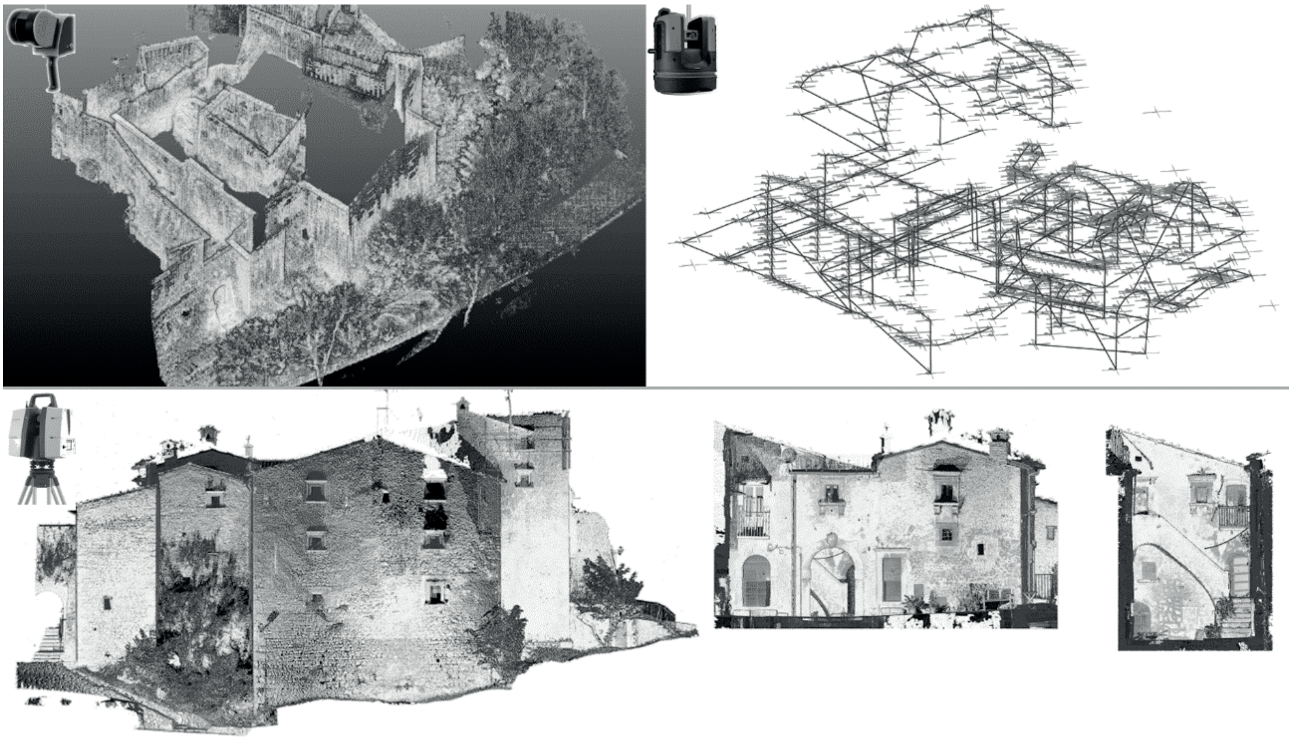

Figure 3 | Survey of the "La Giudea" building aggregate.

Figure 4 | CAD restitution overlaid with photo-plans for the analysis of decay and instabilities.

Finally, the elevations were surveyed using a terrestrial laser scanner, Leica's ScanStation P50, which, through the use of the embedded camera, made it possible to obtain both the point cloud and a photo plane enriched with colour data.

The integration of the data derived from the different survey methods also facilitated specific considerations regarding the state of degradation and the crack pattern of the entire aggregate (Fig. 4) and provided the basis for the digital replica in the BIM environment.

The parametric modelling was performed after a critical analysis of the geometric features identified during the survey phase and on the basis of the semantic decomposition of the components of the building aggregate (Fig. 5) according to their construction, structural, geometric and topological characteristics (Continenza *et al.*, 2016; Savini *et al.*, 2021; Trizio *et al.*, 2021b).

The single components (masonry and floors) were modelled using the libraries available within the software, associating to each of them the data concerning materials and stratigraphy acquired during the knowledge process.

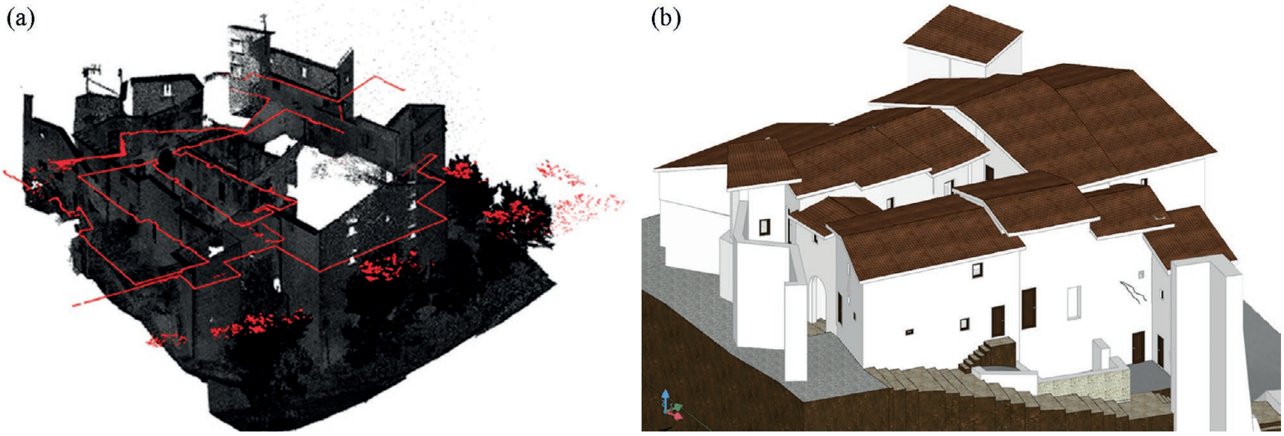

Figure 5 | (a.) Point cloud import into modelling software; (b.) HBIM model of the building aggregate.

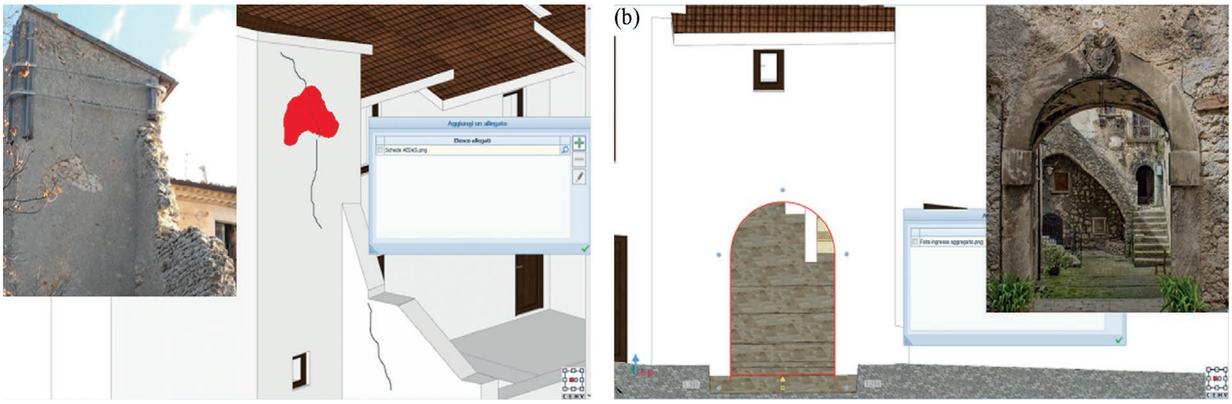

Figure 6 | (a.) Representation in a parametric environment of specific thematic analyses, e.g. forms of degradation; (b.) creation of new parameters for linking data from the knowledge process.

To enrich the model with information related to the specific thematic analyses addressed during the study, the phenomena and instabilities detected were graphically represented through the libraries available in the software (Fig. 6).

Finally, specific parameters were defined to link the architectural model to the photographic and technical documentation obtained, e.g. the AEDeS sheets compiled to define the usability of the single buildings constituting the aggregate, to have a comparison of the data acquired for each element, or building unit, characterising the artefact within the digital replica (Fig. 6).

The parametric model obtained provided the basis for the one used in the structural condition assessments of the aggregate.

4. From the architectural to the structural model

The architectural parametric model was imported into an integrated design environment, popular among designers, with the aim of assessing the structural performance of the aggregate and, at the same time, vertical interoperability between different software (Fig. 7). The structural aggreegate was characterised based on its construction type and class of use according to current regulations (NTC, 2018). Subsequently, information regarding the geographical location was added to identify the reference seismic action parameters. Finally, the achieved knowledge level (KL) and the relative confidence factor (CF) to be used in the evaluation phase were defined (Tab. 1 and 2).

The masonry and related voids generated in the architectural parametric model were created, through an automated procedure, after inputting all the necessary information for the analyses, with the aim of creating the corresponding structural model. In this phase, the

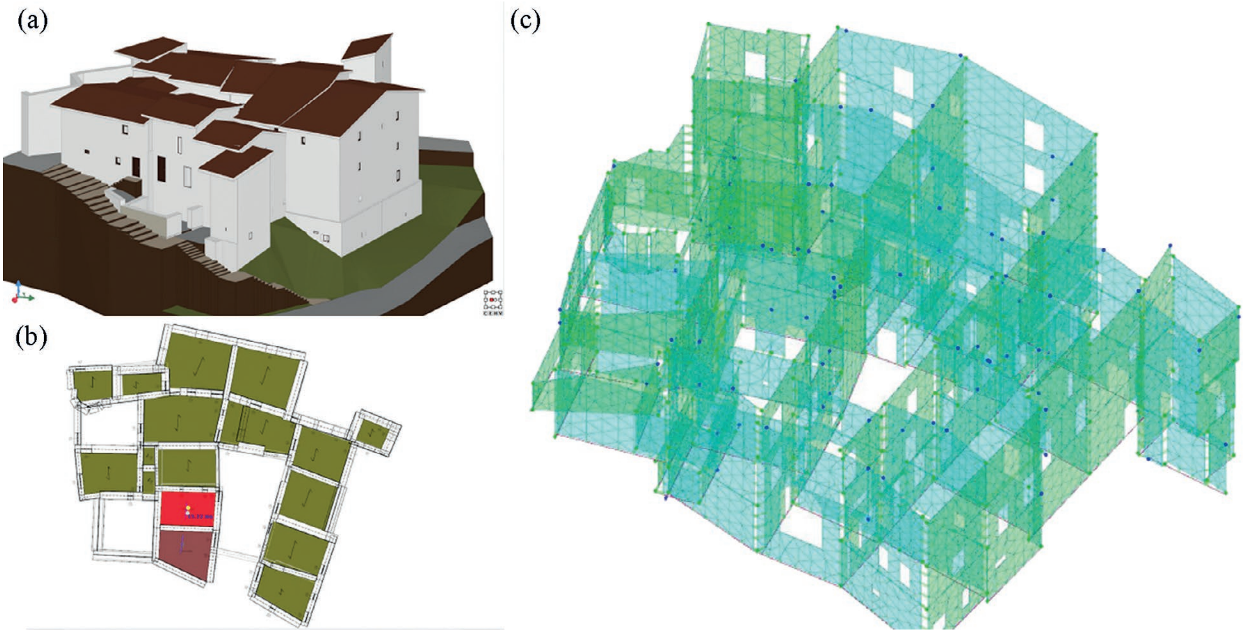

Figure 7 | Structural parametric model creation: (a.) automatic wall detection; (b.) floor modelling; (c.) structural model of the building aggregate.

relevant mechanical properties were assigned to the masonry, assuming, for each identified typology, the reference values for analyses provided in the technical standards of reference (Circular 7, 2019).

All previously created horizons, floors, vaults and roofs were not recognized during model import. Therefore, all the horizontal elements were remodelled in the structural model after defining loads of weight, permanent overload, accidental overload and snow load of single elements.

The model thus updated was the starting point for performing the structural analysis of the aggregate. The available analysis procedures identified different problems related to the stress states of the masonry in the current state, as well as the susceptibility to the triggering of overturning mechanisms in the highest part of the facades due to the lack of proper masonry connections as well as the absence of tie beams, capable of contrasting local mechanisms.

Therefore, appropriate seismic improvement interventions were identified to preserve the historic, architectural, environmental, material, and constructive values of the building, in line with the requirements of current regulations and, in particular, with the PdR (Marra *et al.*, 2019; Fico *et al.*, 2019). Specifically, interventions were considered for reinforcing the masonry through mixtures injections, reinforced repointing of mortar joints, reinforced plaster with composite grids, and reinforced perforations of the corner walls, and for the horizontal structures, by creating a strengthening of composite material at the intrados. In addition, local rebuilding, i.e.

Table 1 | Characteristics of the Building Aggregate, Level of Knowledge and Confidence Factor.

			Topographic Conditions			
Use Category	V_N	Subsoil Category	Category	S_T	Knowledge Level	Confidence Factor
Class 2	50	B	T3	1.20	2	1.20

Table 2 | Seismic hazard parameters of the area.

Limit State	a_g/g	F_O	T^*_C [s]	C_C	T_B [s]	T_C [s]	T_D [s]	S_S
Operational	0.0768	2.378	0.273	1.43	0.130	0.390	1.907	1.20
Damage	0.1005	2.327	0.282	1.42	0.133	0.399	2.002	1.20
Life safety	0.2546	2.364	0.344	1.36	0.156	0.469	2.618	1.16
Collapse	0.3261	2.400	0.360	1.35	0.162	0.486	2.904	1.09

* Reference peak ground acceleration at the site on type A ground (rock).

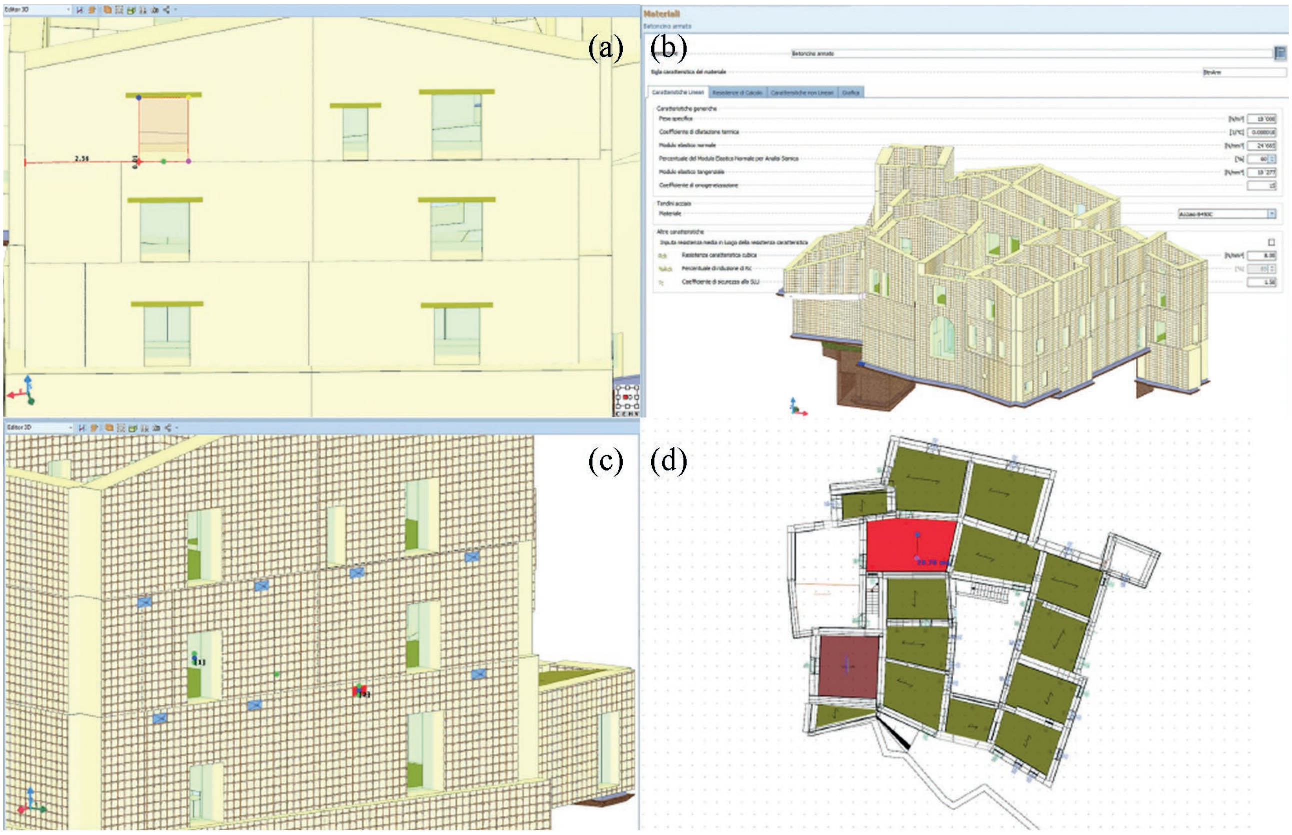

Figure 8 | Strengthening interventions within the structural model: (a.) Placement of steel lintels; (b.) Definition of reinforced plaster properties; (c.) Placement of steel tie rods; (d.) Structural parametric changes.

"stitch and unstitch" in Italian *scuci e cuci*, new steel lintels at openings and tie rods, were also considered.

The interventions for the performance improvement and strengthening of the aggregate were then included within the structural parametric model (Fig. 8). The purpose was to assess their effectiveness and the compatibility of the quantitative objectives in terms of the peak ground acceleration (a_g) values related to the Life Safety Limit State (LSLS).

Therefore, the mechanical characteristics of the masonry were updated in the previous structural model, applying the maximum correction coefficient provided in Table C.8.5.II of Circular 2019 (Circular 7, 2019). At the same time, the stiffness parameters of the strengthened horizontal elements were modified. Finally, new library elements were placed to represent the new steel lintels and tie-rods interventions.

The updated model was subsequently analysed from the structural point of view (NTC, 2018). The results are consistent with the Italian regulations regarding seismic improvement interventions since these interventions ensured an overall performance greater than the 60% of the reference peak ground acceleration level at the Life Safety for new constructions. On this point, it is worth noting that technical and administrative rules for reconstruction and reparation of buildings damaged by earthquakes require a 100% performance only in the case of demolition and reconstruction of the buildings. This is the case of heavily damaged constructions or buildings whose basic seismic resistance baseline is really poor.

On the other hand, it is also clear that a similar rule aims at preventing really invasive works on valuable assets like those belonging to minor historical centres, like the ones showed herein (Fico *et al.*,, 2019; Marra *et al.*, 2019).

5. Discussion and final remarks

The use of digital technologies for the preservation of the historic built environment facilitates the development of reliable processes characterized by high productivity in the area of knowledge, documentation and assessment of structural performance. The several data that become available at the end of the knowledge path defined by the

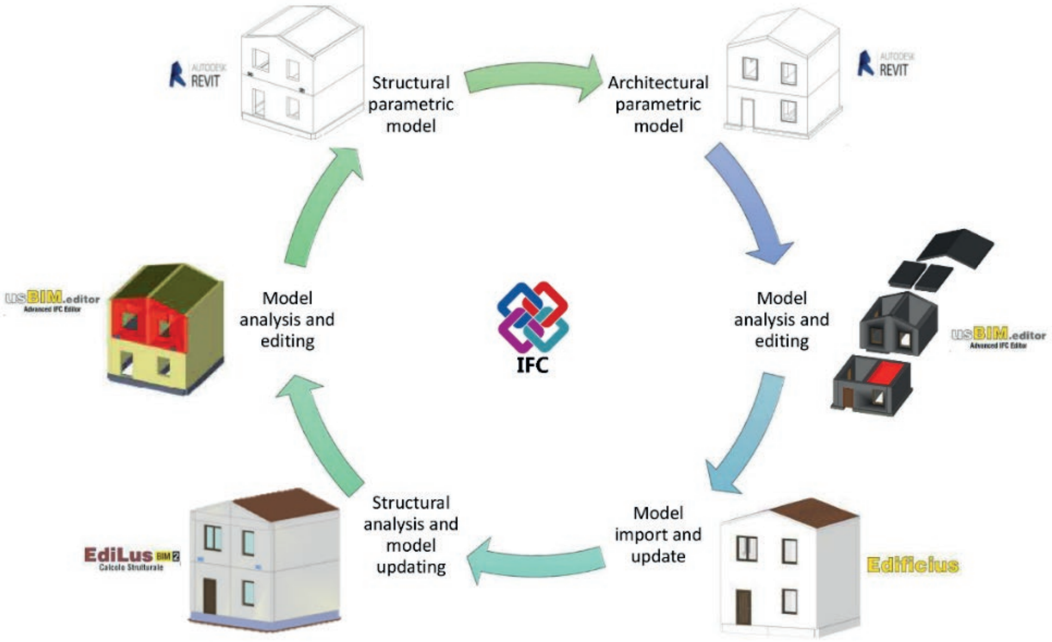

Figure 9 | Operational workflow for interoperability.

different national technical regulations can be collected and managed within digital models. These are conceived as virtual alter egos of the artefact that can facilitate not only the accessibility of information but also the identification of strategies to be implemented from the safety and preservation perspective.

The experience described in this paper, performed in the context of the study and in-depth activities of an academic nature, confirms and well delineates the many benefits of implementing parametric models to support both knowledge process and those related to the analysis and design of structural interventions.

The obtained results confirm the effectiveness of the tools used in the development of HBIM models of complex artefacts characterized by a high level of digital maturity (LOD G), and the availability of tools capable of encouraging the collaboration of the different professionals involved in the recovery and redevelopment process and as a starting point for creating structural models for quantitative analysis.

At the same time, cases of loss of data and information on horizontal structures and singularities in the transition from parametric to structural models have been noted that sometimes dissipate the available information assets and make duplication of modelling operations necessary for structural analyses. These circumstances make clear the need to investigate further the aspects related to the horizontal and vertical interoperability between the different parametric software guaranteed by the IFC format. At the same time, it brings to the attention of the operators the need to proceed with a careful design of the parametric model and of the operational sequences by which modelling is carried out.

In this regard and in relation to some of the problems tested within the experience documented here, Fig. 9 illustrates a workflow centred on the selected software tools.

This workflow has proven capable of overcoming the limitations observed on simple models but needs to be further investigated and validated on models of architectural complexes more articulated and extended. Enduring training and professional updating appear to be crucial references for the consolidation and concrete operational progress of the integrated analysis and design processes of complex artworks, such as those represented by the aggregates widely spread throughout the country. On the other hand, a balance between the flexibility of digital tools to achieve high performance in terms of interoperability, and the rigidity in input and output capable of ensuring high levels of productivity, is not still achieved.

Acknowledgments

The authors are grateful to Pietro Rossi, a graduate of the University of L'Aquila under their supervision, whose enthusiasm and curiosity led to some questions and facilitated the implementation of the process during the thesis preparation. His contribution as a qualified and informed operator of reliable and well-known BIM software packages is therefore acknowledged. The authors also acknowledge the contribution of Andrea Ruggieri, a PhD student at the University of Molise, to the development and processing of the ZEB Horizon laser surveys.

Credits

The research presented is the result of the authors' collective work, continuous discussion and common debate. Adriana Marra wrote sections 3 and 4. Giovanni Fabbrocino supervised the research, revised the work and wrote section 5. Ilaria Trizio supervised the research, revised the paper and wrote sections 1 and 2.

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