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

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.

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
Marra et al.

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

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

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

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 (*prof-ferlo*) 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.

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
Marra et al.

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.

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

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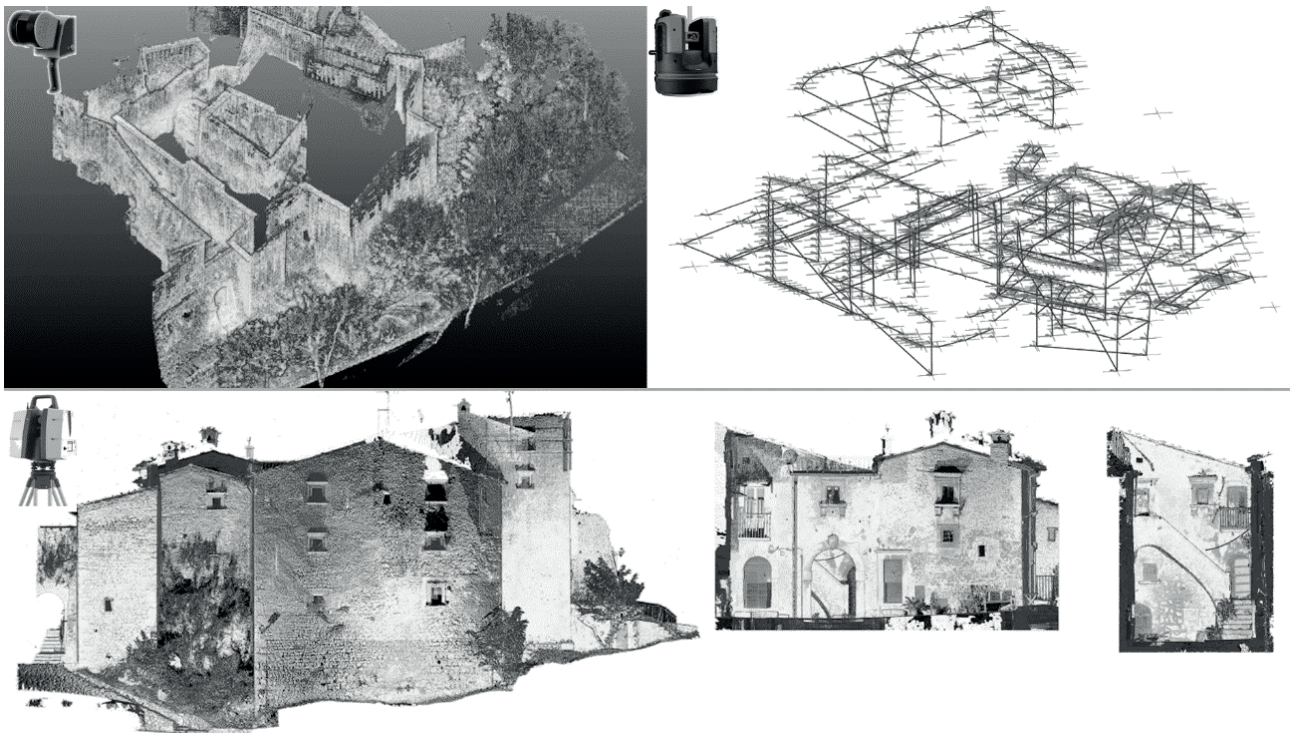*Technology and Sustainability*

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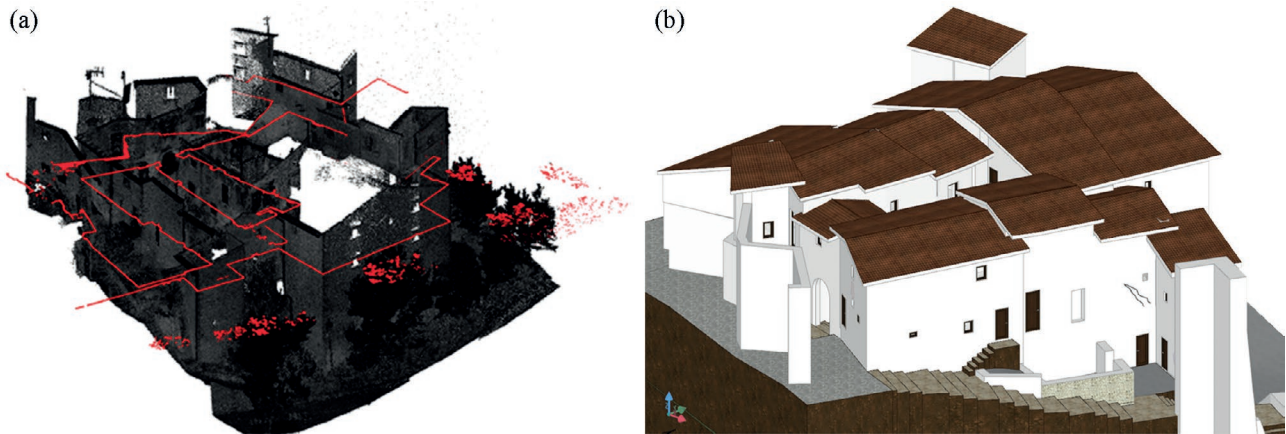
VITRUVIO 8 | Special Issue 1 (2023)
International Journal of Architecture
Technology and Sustainability

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

(a)
(b)

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

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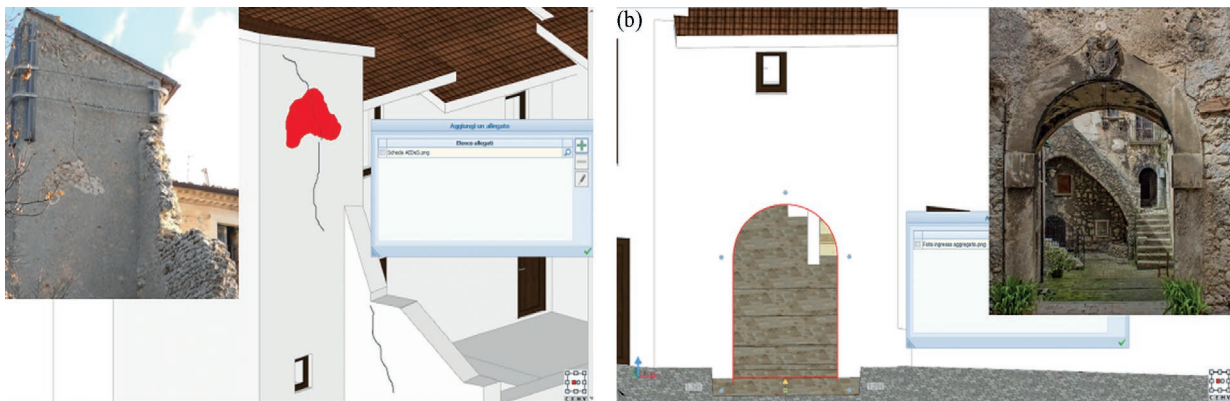
Figure 6 | (a.) Representation in a parametric environment of specific thematic analyses, e.g. forms of degradation; (b.) creation of new parameters for linking data from the knowledge process.

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 aggree gate 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
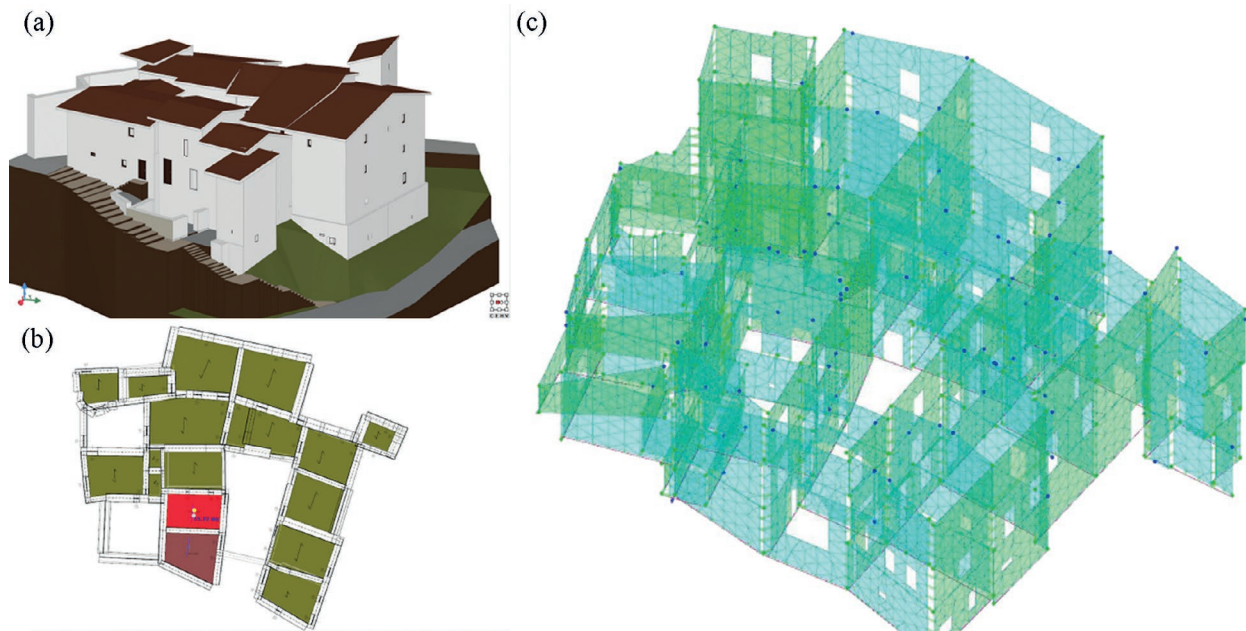
On the interoperability performance of HBIM models for structural conservation and
upgrading of building aggregates in the Italian minor centres
Marra et al.

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

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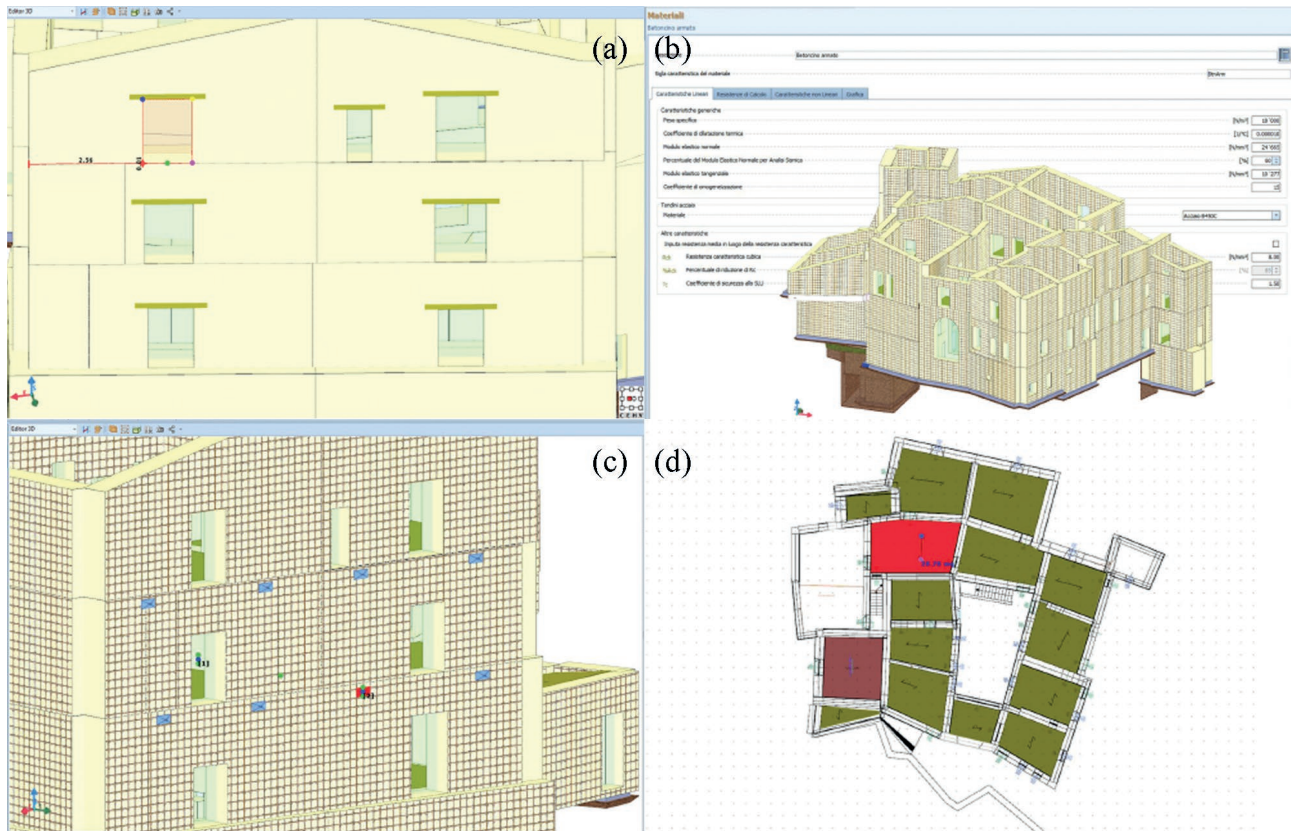
| Use Category | V_N | Subsoil Category | Topographic Conditions | | Knowledge Level | Confidence Factor |
			Category	S_T		
Class 2	50	B	T3	1.20	2	1.20

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).

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
Marra et al.

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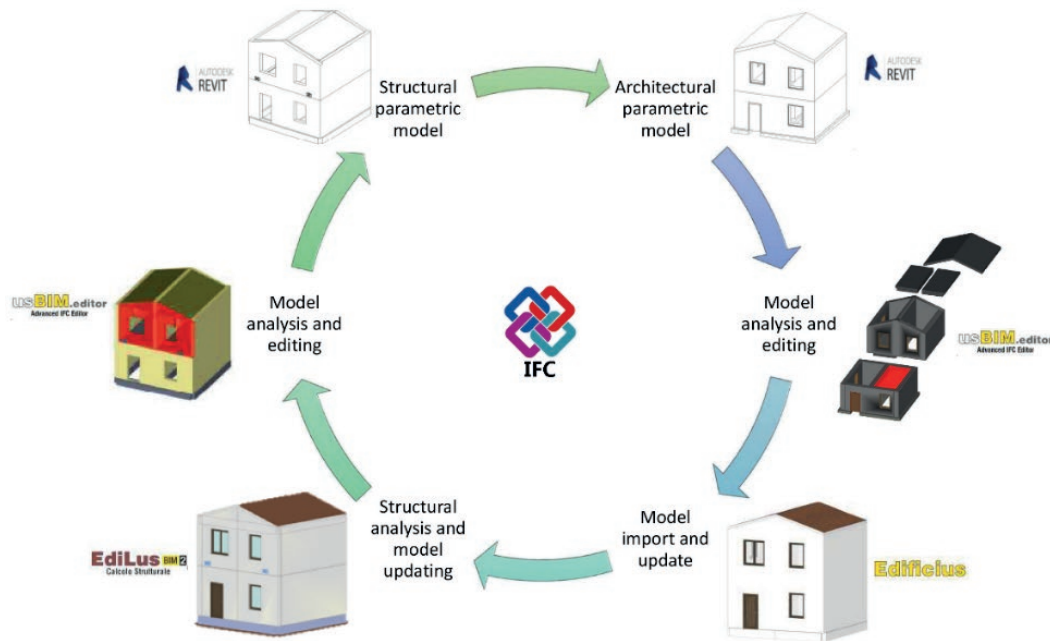
On the interoperability performance of HBIM models for structural conservation and
upgrading of building aggregates in the Italian minor centres
Marra et al.

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

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 identi-
fication 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 encour-
aging 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 architec-
tural 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 interop-
erability, and the rigidity in input and output capable of
ensuring high levels of productivity, is not still achieved.

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
Marra et al.

References

Abbate, E., Invernizzi, S., and Spanò, A. (2022). HBIM parametric modelling from clouds to perform structural analyses based on finite elements: A case study on a parabolic concrete vault. *Applied Geomatics*, *14*, 79-96. https://doi.org/10.1007/s12518-020-00341-4

Bartolomucci, C. (2020). Spopolamento e abbandono nei paesi montani d'Abruzzo: degrado e risorsa. Un processo reversibile? *ArcHistoR*, 7(13), 1694-1721. https://doi.org/10.14633/AHR290

Bartolomucci, C., and Donatelli, A. (2012). La conservazione nei centri storici minori abruzzesi colpiti dal sisma del 2009: esigenze di riuso e questioni di conservazione. In G. Biscontin and G. Driussi (Eds.), *La Conservazione del Patrimonio Architettonico All'aperto: Superfici, Strutture, Finiture, Contesti* (pp. 101-111). Arcadia Ricerche.

Bartolomucci, C., Bonzagni, D., and Trizio, I. (2012). Restauro e valorizzazione dei centri storici dopo il sisma del 2009: un GIS 3D per il progetto di reintegrazione delle lacune urbane. En *16° Conferenza Nazionale ASITA, Atti* (Fiera di Vicenza, 6–9 novembre 2012) (pp. 159-166). Sl, sn.

Bronzino, G.P.C., Del Giudice, M., Osello, A., and Zerbinatti, M. (2019) "Casa Bossi a Novara", approccio HBIM per la gestione semi-automatica del cantiere di conoscenza. In: P. Belardi (ed.), *Riflessioni. L'arte del disegno/Il disegno dell'Arte*. Gangemi Editore, Roma. pp. 439-448.

Brumana, R., Stanga, C., Previtali, M., Landi, A.G., and Banfi, F. (2020) Wrap-Up Synthesis Model from High-Quality HBIM Complex Models, and Specifications, to Assess Built Cultural Heritage in Fragile Territories (Arquata Del Tronto, Earthquake 2016, the Church of St. Francesco, IT). In: M. Ioannides, E. Fink, L. Cantoni and E. Champion (eds), *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection. EuroMed 2020. Lecture Notes in Computer Science*, vol 12642. Springer, Cham, pp. 100-111. https://doi.org/10.1007/978-3-030-73043-7_9

Brumana, R., Della Torre, S., Oreni, D., Cantini, L., Previtali, M., Barazzetti, L., and Banfi, F. (2018) SCAN to HBIM-post earthquake preservation: Informative model as sentinel at the crossroads of present, past, and future. In: M. Ioannides, E. Fink, R. Brumana, P. Patias, A. Doulamis, J. Martins and M. Wallace (eds.), *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection 7th International Conference, EuroMed 2018*. Springer, Cham. pp.39-51. https://doi.org/10.1007/978-3-030-01762-0_4

Bruno, S., De Fino, M., and Fatiguso, F. (2018) Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management. *Automation in Construction, 86*, 256-276. https://doi.org/10.1016/j.autcon.2017.11.009

BuildingSMART (2022). Industry Foundation Classes (IFC). https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/. (accessed 03 September 2022).

Circular 7 (2019) *Guidelines for the application of the updating of the technical standards for construction provided by the Ministerial Decree of 17 January 2018*. G.U. n. 35 11/02/2019, Roma, in Italian.

Continenza, R., Trizio, I., Giannangeli, A., and Tata, A (2016) HBIM for restoration projects: case-study on San Cipriano Church in Castelvecchio Calvisio, Province of L'Aquila, Italy. *DisegnareCON, 9*(16), 15.1-15-9.

Currà, E., D'Amico, A., and Angelosanti, M. (2021) Representation and knowledge of historic construction: HBIM for structural use in the case of Villa Palma-Guazzaroni in Terni. *Tema, 7*(1), 8-20. https://doi.org/10.30682/tema0701b

Della Torre, S. (2017) Un bilancio del progetto BHIMM. In Modellazione e gestione delle informazioni per il patrimonio edilizio esistente. *Ingenio*, 10-16.

Doria, E., Morandotti, M., and Venini, P. (2018). Conoscenza e progetto per il riuso di spazi esistenti: un caso di studio. In: F. Mutoli (ed.), *ReUSO 2018. L'intreccio dei saperi per rispettare il passato interpretare il presente, salvaguardare il future*. Gangemi Editore, Roma. pp. 1549-1560.

Fico, R., De Martino, G., Marra, A., Pecci, D., Sabino, A., Di Ludovico, M., Mannella, A., Speranza, E., Prota, A., and Dolce, M. (2019). Building aggregates of historical centers: damage analysis and preliminary remarks on reconstruction costs of the Municipalities of the Crater affected by the 2009 L'Aquila earthquake. In: F. Braga, A. Dall'Asta and F. Gara (eds.), *Atti del XVIII Convegno ANIDIS "L'Ingegneria Sismica in Italia"*. Pisa University press, Pisa, pp. SS07: 93-103.

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

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

Fiorani D. (2017) La modellazione della conoscenza nel restauro: uno sviluppo per il BHIMM. In: S. Della Torre (ed.), *Modellazione e gestione delle informazioni per il patrimonio edilizio esistente-Built Heritage Information Modelling/Management BHIMM*. Galazzano, Edizioni IMRead. pp. 7-12.

Gerbino, S., Cieri, L., Rainieri, C., and Fabbrocino, G. (2021) On BIM Interoperability via the IFC Standard: An Assessment from the Structural Engineering and Design Viewpoint. *Applied Sciences, 11*(23), 11430. https://doi.org/10.3390/app112311430

La Russa, F. M., Intelisano, M., Galizia, M., Caliò, I., and Santagati, C. (2022). "An expeditious parametric approach for City Information Modeling and Finite Element Analysis". *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVI-2/W1-2022, 307–314. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-307-2022

Lanzara, E., Scandurra, S., Musella, C., Palomba, D., di Luggo, A., and Asprone, D. (2021) Documentation of structural damage and material decay pehnomena in H-BIM systems. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVI-M-1-2021, 375-382. https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-375-2021

Magistri, P. (2013) La Via degli Abruzzi: un itinerario storico-geografico. *Documenti geografici, 2*-2013, 69-81.

Marra, A., Sabino, A., Fico, R., Pecci, D., Gualtieri, R., Mannella, A., and Fabbrocino, G. (2019). Conservation of historical minor centers hit by L'Aquila earthquake in the context of the reconstruction process. In: F. Braga, A. Dall'Asta and F. Gara (eds.), *Atti del XVIII Convegno ANIDIS "L'Ingegneria Sismica in Italia"*. Pisa University press, Pisa, pp. SG13:160-170.

Marra, A., Trizio, I., and Fabbrocino, G. (2021) Digital Tools for the Knowledge and Safeguard of Historical Heritage. In: C. Rainieri, G. Fabbrocino, N. Caterino, F. Ceroni and Notarangelo M.A. (eds), *Civil Structural Health Monitoring. CSHM 2021. Lecture Notes in Civil Engineering*, *156*. pp. 645–662. https://doi.org/10.1007/978-3-030-74258-4_41

Marson, C., Taffarel, S., Bettiol, G., Munari, M., Modena, C., Cialone, G., Cifani, G., Mannella, A., and Petracca, A. (2013). Sviluppo dei Piani di Ricostruzione di borghi dell'aquilano colpiti dal sisma del 6 aprile 2009. In: *ANIDIS 2013, L'ingegneria Sismica in Italia, Padova, Italia, Conference Proceedings*.

Messaoudi, T., Véron, P., Halin, G., and De Luca, L. (2018) An ontological model for the reality-based 3D annotation of heritage building conservation state. *Journal of Cultural Heritage, 29*, pp. 100-112. https://doi.org/10.1016/j.culher.2017.05.017

MIBACT - Ministero per i Beni e le Attività Culturali. Segretariato Generale (Eds.) (2011). *Directive of the Prime Minister, 09/02/2011. Guidelines for the assessment and the mitigation of seismic risk of cultural heritage with reference to Italian NTC2008. G.U. n. 24* 29/01/2011. Gangemi Editore, Roma, in Italian

NTC (2018). *Ministerial Decree January 17, 2018. Updating of Technical Standards for Construction*. *G.U. n. 42 20/02/2018*, Roma, in Italian

Oreni, D., Brumana, R., Della Torre, S., and Banfi, F. (2017) Survey, HBIM and conservation plan of a monumental building damaged by earthquake. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-5/W1, pp. 337–342. https://doi.org/10.5194/isprs-archives-XLII-5-W1-337-2017

Pepe, M., Costantino, D., and Restuccia Garofalo, A. (2020) An efficient pipeline to obtain 3D model for HBIM and structural analysis purposes from 3D point clouds. *Applied Sciences, 10*(4), p. 1235. https://doi.org/10.3390/app10041235

Saccucci, M., and Pelliccio, A. (2018). Integrated BIM-GIS System for the enhancement of urban heritage. In: *2018 Metrology for Archaeology and Cultural Heritage (MetroArchaeo)*. IEEE, pp. 222-226. https://doi.org/10.1109/MetroArchaeo43810.2018.13625

Savini, F., Fabbrocino, G., and Marra, A. (2021) Digitization of historical architectural elements, a workflow for knowledge of minor centers in inner areas. *DisegnareCON, 14*(26), pp. 9.1-9.15. https://doi.org/10.20365/disegnarecon.26.2021.9

Trizio, I., Continenza, R., and Tata, A. (2017) Riscoperta del palazzo della famiglia Branconio in L'Aquila. Applicazioni BIM a un cantiere della ricostruzione aquilana. In: A. Di Luggo, P. Giordano, R. Florio, L.M. Papa, A. Rossi, O. Zerlenga, S. Barba, M. Campi and A. Cirafici (eds.), *Territori e frontiere della rappresentazione, 39° Convegno Internazionale dei Docenti delle Discipline della Rappresentazione*. Gangemi, Roma. pp. 1659-1666.

Trizio, I., Savini, F., Giannangeli, A., Boccabella, R., and Petrucci, G. (2019). The Archaeological Analysis of Masonry for the restoration project in HBIM. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W9, pp. 715-722. https://doi.org/10.5194/isprs-archives-XLII-2-W9-715-2019

Trizio, I., Marra, A., Savini, F., and Fabbrocino, G. (2021a) Survey Methodologies and 3D Modelling for Conservation of Historical Masonry Bridges. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, VIII-M-1-2021, pp. 163–170. https://doi.org/10.5194/isprs-annals-VIII-M-1-2021-163-2021

Trizio, I., Marra, A., Savini, F., and Ruggieri, A. (2021b). The Vernacular Architecture and its Languages: Towards an Ontology of the Minor Historic Centres. In: A. Arena, M. Arena, D. Mediati and P. Raffa (eds.), *Connecting - Drawing for Weaving Relationships. Languages, Distances, Technologies*. Franco Angeli, Milano. pp. 1198-1215.