Virtual Archaeology Review, **13**(26): 1-21, 2022
https://doi.org/10.4995/var.2022.15313

Received: March 24, 2021
Accepted: May 17, 2021

BUILDING ARCHAEOLOGY INFORMATIVE MODELLING TURNED INTO 3D VOLUME STRATIGRAPHY AND EXTENDED REALITY TIME-LAPSE COMMUNICATION

MODELIZACIÓN DE LA INFORMACIÓN DE LA ARQUEOLOGÍA DE LA CONSTRUCCIÓN TRANSFORMADA EN ESTRATIGRAFÍA VOLUMÉTRICA 3D Y COMUNICACIÓN DE REALIDAD EXTENDIDA CON INTERVALOS DE TIEMPO

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Highlights:

- 3D survey and scan-to-HBIM process for the creation of a digital twin were oriented to the preliminary design of the preservation plan of the church of St. Francesco in Arquata del Tronto (Italy).
- Stratigraphy is investigated and oriented towards a digitisation process to share different levels of knowledge through new forms of digital-sharing such as Common Data Environment (CDE) and cloud-based BIM platform.
- eXtended reality (XR) is the final tool to reach new communication levels and a wider audience characterised by experts in the construction sector and virtual and non-expert tourists.

Abstract:

This paper describes the case study of the damaged church of St. Francesco in the Arquata del Tronto (Italy), struck by the earthquake in 2016. The municipality commissioned the research to support the preliminary design of the preservation plan. The first digitisation level has been performed from the richness of surveying data, acquired from static and dynamic terrestrial laser scanning (TLS), as well as photogrammetry; overcoming challenging constraints was necessary due to the scaffolding covering the surfaces. The geometric survey allowed authors to acquire massively geometric and material information supporting the three-dimensional (3D) volume stratigraphic and the creation of the Heritage Building Information Modelling (HBIM). The authors propose a shift from the Geographic Information System (GIS)-based analysis of the materials toward spatial HBIM management. Building Archaeology is turned into HBIM 3D volume stratigraphy, overcoming the bidimensional (2D) surface mapping, in favour of a 3D understanding of direct and indirect sources. Material mapping is added to HBIM 3D volume stratigraphy, and each stratigraphic unit (SU) has its proprieties. The 3D volume stratigraphic database has been designed to collect the data on the unit detection at three levels (direct sources data collection, indirect data documentation, the relation among the BIM object elements). A common data environment (CDE) was set up to share the 3D volume informative models that can be accessed, including all the information gathered. The knowledge transfer using the eXtended Reality (XR) potentiality improves citizen and tourist experience, enhancing the comprehension of difficult concepts like the SUs to support a better critical 3D reconstruction. It includes the phases of construction across time-lapse documentation that validates related information within the building archaeology informative models leaving spaces to the uncertainty and documenting the relationship established so far thanks to the direct and indirect sources. The result obtained is a live digital twin that can be continuously updated, which justifies the costs and time demand of HBIM despite 2D drawings.

Keywords: building archaeology; stratigraphic unit (SU); HBIM; informative models; 3D volume stratigraphy; digitisation

Resumen:

Este artículo describe el caso de estudio de la iglesia con daños de San Francisco en Arquata del Tronto (Italia), que fue afectada por el terremoto de 2016. El municipio encargó la investigación que apoyará el diseño preliminar del plan de conservación. El primer nivel de digitalización empezó a partir de la amalgama de datos topográficos adquiridos mediante escáner láser terrestre (TLS) dinámico y estático, y fotogrametría, superando las desafiantes limitaciones ocasionadas por los andamios que cubren las superficies. El levantamiento geométrico permitió a los autores capturar información geométrica y material de manera masiva que respalda el volumen estratigráfico tridimensional (3D) y la creación del modelado de información de edificios patrimoniales (HBIM). Los autores proponen el cambio del análisis de los materiales basado en los sistemas de información geográfica (SIG), a la

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gestión espacial HBIM. La arqueología de la construcción se convierte así en estratigrafía volumétrica HBIM 3D, superando el mapeado de la superficie bidimensional (2D) en favor de una comprensión 3D de las fuentes directas e indirectas. El mapeado de los materiales se añade a la estratigrafía volumétrica 3D en HBIM, y cada unidad estratigráfica (UE) tiene sus propiedades. La base de datos 3D volumétrico-estratigráfica ha sido diseñada para capturar los datos en tres niveles (recopilación de datos de fuentes directas, documentación de datos indirectos, relación entre los elementos del objeto BIM). Se ha configurado un entorno de datos común (CDE - Common Data Environment) que comparte los modelos informativo-volumétricos 3D al que se puede acceder, así como toda la información compilada. La trasmisión del conocimiento usando la realidad extendida (XR - eXtended Reality) logra potencialmente una mejor experiencia para la ciudadanía y las personas en visita turística, potenciando la comprensión de conceptos difíciles como son las unidades estratigráficas que apoyan una mejor reconstrucción crítica en 3D. Se incluyen las fases de construcción a través de la documentación temporal que valida la información relacionada dentro de los modelos informativos de la arqueología de la construcción, dejando espacios a la incertidumbre y documentando la relación establecida hasta el momento gracias a las fuentes directas e indirectas. El resultado obtenido es un gemelo digital en vivo que se puede actualizar continuamente, que justifica los costes y el tiempo que exige el HBIM a diferencia de los dibujos 2D.

Palabras clave: arqueología de la arquitectura; unidad estratigráfica; HBIM; modelos informativos; estratigrafía volumétrica 3D; digitalización

1. Introduction

Heritage building information models (HBIM) need to enter a mature era of the commonly adopted system. To this aim, they are required to address and support the generation of informative content models boosting their specificities, overcoming limitations of traditional representation for the preservation plans, gearing the communication of the gained informative levels. Among the most common system to manage the preservation plan, GIS-based analysis of materials and construction techniques (and decay) have been fostered since digital rectified images and orthophotos have been massively introduced starting from the 1990s. It enhanced the control of metric computation and cost estimation through database correlation to the geographic entities (i.e. price lists of the restoration works). The paper introduces the potentials of using building archaeology turned into HBIM 3D volume stratigraphy, thus overcoming the logic of the 2D surface mapping in favour of a spatial three-dimensionality of the representation of the stratigraphic units (SUs). It generates BIM-enabled units to host the richness of the information and locally refer to the density of punctual information patiently collected from the analysis of the direct and indirect sources coming from the building archaeology. The development of a common data environment (CDE) platform allows access to the HBIM. The richness of the informative content models and knowledge has been transferred toward a better informed Extended reality (XR) allowing better fruition by the citizens. The spatial dimension of the building archaeology applied to informative models gained a 3D volume stratigraphy to enhance XR feeding implemented for communication purposes using time-lapse models. The result is a first step in analysing the preliminary design plan that the definitive and executive levels could enhance. A dynamic instrument able to follow the description of the phases of the construction site. Furthermore, it is a first construction phase representation highlighting fascinating and complex aspects characterising the church's history to communicate to citizens. It tries to unveil some aspects, such as the church as two connected naves, with different altars, or the three main phases, with their lights and shadows, documented by the building archaeology.

2. Research objectives

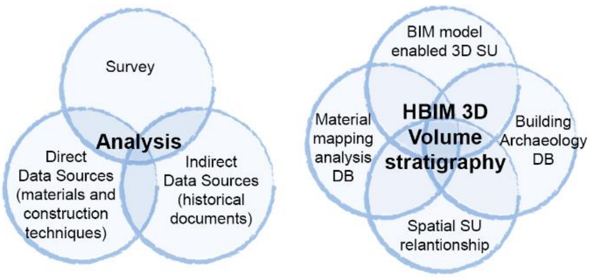
The dense history of the church of St. Francesco and the richness of the historical research allowed to get a more in-depth information level explaining the correlation of the church within its strategic position during the Roman period (Via Salaria) and crossing many historical phases for which the application of 3D volume stratigraphy that embedded the acquired data, still accessible after the research or the restoration (Section 3). In recent years, interesting studies tried to go beyond simple 3D representation and orient the modelling of SUs to support the archaeologic excavation for archaeology research management (ARM), heterogeneous datasets in HBIM of decorated surfaces and information modelling for the communication of historical phases subtraction process (Heesom et al., 2021; Lerma et al., 2010; Reina et al., 2019, Stanga et al., 2017; Valente et al., 2017). Furthermore, different HBIM based approaches enabled objects to manage the material mapping when belonging to 3D complex objects has been proposed and applied to the Basilica di Collemaggio (Brumana et al., 2018; Kivilcim & Duran, 2021; Nieto et al., 2021; Valinejadshoubi et al., 2018). In this context, this study intends to exploit and improve those aspects toward the specificity of the building archaeology application with HBIM (Section 4). HBIM volume stratigraphy database was defined to cross the unit's detection at three levels (Fig. 1):

(i) the direct sources exploited so far (description of materials, construction technique, stones dimensions, stone surface finishing);

(ii) the description of the indirect sources (archive documentation and reports, historical maps and pictures);

(iii) the relation among the BIM object elements.

It allows to avoid a rigid dating grid that is often not possible nor validated, in favour of the possibility of an adaptable instrument capable of documenting the data acquired so far in terms of facts and hypothesis, toward a logic of possible connections, where and when possible, but at the same time leaving opened unclarified aspects from which the phases of construction cannot be defined. The added value is represented by the possibility of cross-relating the viewable foreground units with the background units and the adjacent ones in a spatial dimension. It also opens the way toward in-depth learning-based analysis relating the units' levels and positions, possibly correlating them with the geographic areas' construction techniques (Section 5).



(a) (b)

Figure 1: (a) Direct and indirect data sources integration with the surveying; (b) HBIM 3D volume stratigraphy through Database (DB) and Stratigraphic Units (SU).

The bet is to transform such instrument in a digital live twin extended to the whole multi-temporal spatiality for the preservation plan analysis, that can be managed during the construction site, but also accessible by a common spatial environment to support co-working experts within the preservation design process and also for historical purposes (Fig. 2). The church's digitisation presented many challenges due to the scaffolding set up to guarantee safety and accessibility in the assessment phase. The integration of TLS carried it out with Simultaneous Location and Mapping (SLAM) based mobile mapping systems allowing the operators to set up walking closed paths, overcoming the limitation of the short distances constraints of the planks and the surveying of external areas of the church and the cloister so far not yet put in safety (Section 3). On the richness of the massive data collected (pictures and point clouds) and the church damaged surfaces, an HBIM model object generation made available the support on which to deploy the generation of HBIM enabled SUs specifically (Section 6).

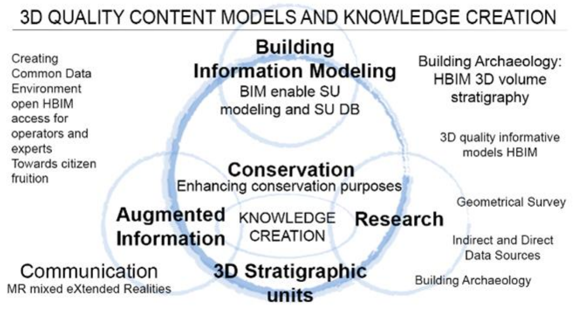


Figure 2: The methodological workflow: from data sources to HBIM 3D volume stratigraphy empowering knowledge creation to enhance preservation purposes and citizen fruition

3. Framework

3.1. Historical background

Arquata del Tronto still today suffers from its border position –between territories with different past, economy and administration– being wedged between the Sibillini and Laga mountains, in a territory unsuitable for agriculture and industrial settlement. The economic prosperity that characterised Arquata between the Roman Empire age and the early Middle Ages is mostly due to the presence of the ancient Roman road called Via Salaria: Arquata was founded at the top of one of the few mountain passes that provided an easy passage from the Adriatic Sea to Rome, the capital of the empire. Preceded by an earlier settlement, the town named Surpicatum rapidly developed under the Roman Empire. The control of traffic along the Via Salaria constituted the main income for the small town that was soon quarrelled by the contiguous towns of Ascoli and Norcia between the 13th and 15th centuries (Galiè & Vecchioni, 2006). The condition of prosperity would benefit Arquata for the whole 16th century until the development of agriculture in the neighbouring flat regions and the creation of other commercial communication routes entailed the progressive decline of Arquata culminating in the dramatic earthquake in 1703 (Comino 1996; Comino 2000): a great part of the town buildings were damaged and destroyed. The Papal State, wide and irregular, assigned Arquata the role of the territorial garrison at the southern border, where bandits and a "frontier economy" were tolerated; such role continued to exist throughout the whole 19th century culminating in considerable migratory flows towards other continents and the newborn capital, Rome. In 1861 the annexation to the Kingdom of Italy involved a gradual shift of the borders, relegating Arquata to the centre of an even more marginal and isolated territory in the Marche region (Anselmi, 1977): the modernisation of the road infrastructure (Ciociola & Castelli, 2010), the construction of the first public buildings (schools, hospitals...), the economy based on hiking and agritourism, however, did not stop the demographic decrease, which is still ongoing today. Therefore, in the Middle and Modern Ages, Arquata has experienced its period of greatest economic prosperity, as proved by its rich artistic and architectural heritage still existing today. The foundation and development of the Franciscan settlement in the hamlet of Borgo is significant evidence of this peculiar articulated history. The settlement is located near the ancient Via Salaria which went up to Arquata and its stronghold from the ancient church of S. Maria della Pieve (currently named SS. Salvatore): although it is by now certain that Franciscan monasteries played a very important role in the construction of medieval towns, in the smaller towns of Umbria region, the foundation outside the city walls, near the gates or the suburbs (Czortek, 2007) was very common: in this case, the Franciscan complex was built to host and take care of the travellers walking along the Via Salaria. Here a first settlement of the Franciscan friars, in the Provincia Serafica –Custodia di Regno (which included eight other convents) is attested by Father Agostino di Stroncone in 1251 (Di Stroncone, 1887); however, the archival documents mention a church of the Minors only forty years later, in a decree by Pope Nicholas IV (Ciociola, 2010). The events of the convent and the Franciscan church are still little known today, partly due to the dispersion of the archive; however, it is possible to identify three significant building phases which, from the first small church led to the construction of a church with a single hall, a square choir without side chapels, corresponding mainly to the north aisle, in the 14th century. The addition of a second nave is dated between the 16th and the first half of the 17th century. The dating of the bell tower (*campanile a vela*) is still uncertain, but the refined ashlar masonry in the base refers to ancient construction techniques, perhaps leading back to the first settlement. Numerous earthquakes and continuous maintenance have resulted in significant interventions on the building, as well as the 20th-century restorations, with the introduction of reinforced concrete structures and the complete replacement of the roof. Finally, the earthquake of August-October 2016 and the heavy snowfall in January 2017 caused the collapse of the roof, of the wooden carved ceiling and, in part, of the walls (Fig. 3). Considering this complex situation, the Municipality of Arquata del Tronto has entrusted the Politecnico di Milano (responsible prof. Arch. A. Grimoldi) with a research programme in support of the restoration and reconstruction project.

(a)

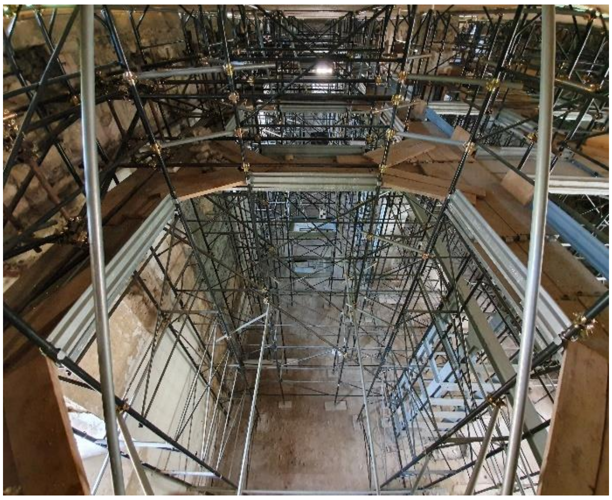
(b)

Figure 3: a) Arquata del Tronto before and after the 6.0 magnitude earthquake (2016); b) Aerial view of the church after the earthquake: the main structures and the roof of the building collapsed. Source: © Google LLC.

3.2. 3D survey

The geometrical survey of the church was carried out in two different survey campaigns and epochs. Due to the complexity of the surveying conditions (i.e. temporary safety scaffolding are currently used to put in safety the church and are occluding large portions of the inner part of the church) a geodetic network was established to allow a strong reference for the alignment of the scans acquired (Fig. 4).

(a) (b)



(c)

Figure 4: Church of St. Francesco: a) The interior of the building before the earthquake; b) After the earthquake © ing. Romeo Mariani; and c) Complexity of the surveying conditions after the earthquake with temporary safety scaffolding.

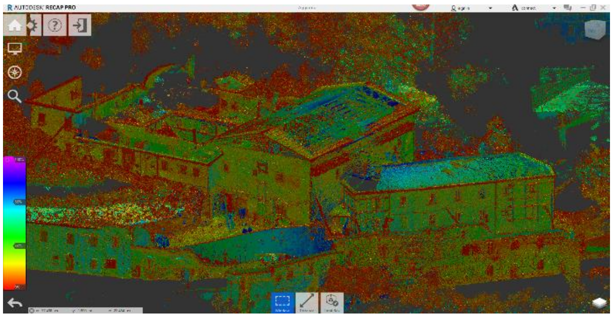
In particular, the geodetic network established is composed of eight stations, four inside the church and four outside and in the surrounding areas. In particular, the stations inside the church were located at different levels of the safety scaffolding to allow a good connection among the scans acquired at different levels. The selection of the stations in the different scaffolding level was challenging due to the difficulty in identifying stable points. For this reason, a specific mounting for the total station was specifically built to be used to fix the total station in correspondence with the stable anchoring of the scaffolding.

Multiple connections between inside and outside stations were established to guarantee a good redundancy to the network. The network was measured with Leica TPS1200 total station and a final least-squares adjustment provided an average precision of ±2.0 mm. To capture the state of the church after the earthquake and have an evaluation of the damages a static TLS survey was planned. Also for this survey, the issue of identifying stable points at different levels of the scaffolding was solved using a special mounting to be anchored at the standard of the scaffolding (Fig. 5).

To survey the entire church 65 scans were acquired by using a Faro Focus 3D. The final registration (Faro SCENE 6.2.30) of the scans provided an average precision of the target of ±4.5 mm (Fig. 6).

(a)

(b)



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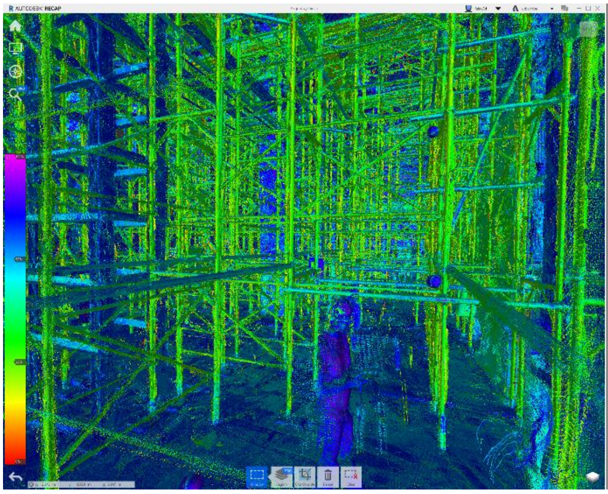


(d)

Figure 5: TLS survey: a) use of a special mounting to identify reference points; b) main façade of the church; c) 65 scans of the church in Autodesk Recap Pro; and d) view of the interior point clouds.

During the first acquisition epoch, it was not possible to perform a static laser scanning acquisition in some areas of the complex. Indeed, due to safety issues, it was not possible to station in some areas for more than three minutes and this prevented the survey of those areas with a static TLS. A second surveying campaign was planned with a handheld Mobile Mapping System (MMS) to cope with this limitation. The main advantage of "scan while walking" allowed by an MMS was the possibility to respect the safety constraints. During the second epoch, the survey was carried out by the MMS GeoSLAM ZEB-HORIZON (Fig. 7 and Table 1).

Figure 6: Pairwise registration precision matrix. The matrix is evaluated considering residuals on targets (green: residuals < 5.0 mm, orange: 5.0 mm < residuals < 10.0 mm, red: residuals > 10.0mm).

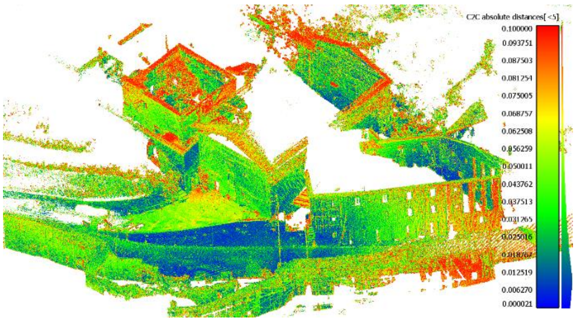
Figure 7: Data acquisition: a) GeoSLAM ZEB-HORIZON plus helmet; and b) around the church.

Table 1: Some technical data of ZEB-HORIZON.

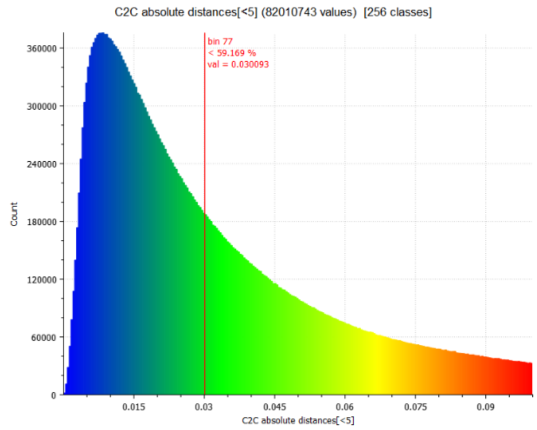
LiDAR device	Velodyne VLP-16
Wavelength	903 nm
Eye-safe laser	Class 1
Singe point precision	1 – 3 cm
Acquisition speed	300000 pts/s
Max. Range	100 m
Rotation	10 Hz
Weight	1.3 kg

To complete the survey, four acquisitions were designed. To allow registration with the acquisition carried out at epoch 1 a large overlap (60%) was kept between the two epochs in the outer area of the church. The different SLAM acquisitions were registered among them using the non-rigid registration (based on SLAM re-computation provided) within GeoSLAM Hub v. 5 software.

The rigid Iterative Closest Point (ICP) was used for the registration of the SLAM acquisitions with the static TLS data. Results of the registration in the overlapping area, 60% of the points present a distance lower than 3.0 cm, that is the single point precision of the instrument, and 80% below 5.0 cm (Fig. 8). This proves the good alignment of the scans acquired in the two epochs.



(a)



(b)

Figure 8: Registration results: a) SLAM point cloud colourised with pointwise distances with respect to the static TLS data; and b) distribution of discrepancies (bottom).

4. Building archaeology of the façade: from 3D survey and historical records

4.1. Primary and secondary data sources for building archaeology

The study of buildings benefits from the contribution of direct and indirect sources. In broad terms, direct (or primary) sources provide first-hand information about a relevant fact for a given historical reconstruction. In architectural research, geometrical surveys, on-site inspection, and material/decay analysis are the most common direct sources. Indirect (or secondary) sources are reconstructions from primary and/or other secondary sources, such as reports and analysis of scholars' past evidence. The "primary" sources are usually considered more "factual" or descriptive, whereas the "secondary" ones include the investigator's interpretations. However, both direct and indirect sources contain values and elements of interpretation. Thus, the distinction between direct and indirect sources is not that one is "fact" and the other "interpretation". It is essential to understand the context in both cases: where and when the information was produced? By whom? For what purpose? Based on what knowledge? Although starting from the object's direct analysis, building archaeology is intertwined with indirect sources to understand architectural artefacts better. It is a borderline discipline between architecture and archaeology, but it involves many other factors, such as the historical, artistic, cultural, socio-economic values, and the material culture embedded in the building. If this way of being on edge among various sectors is a strength, on the one hand, it is a weakness because it labelled building archaeology as an ancillary discipline. In Italy, building archaeology practical and theoretical bases were set around 1987. In the 1990s, the debate around the discipline shifted to various issues that relate to building archaeology to restoration; materials, construction techniques, and building types; the history of art; historical interpretation; urban planning (Brogiolo, 2002; Brogiolo & Cagnana, 2012, Della Torre, 2012). Although in the beginning, the idea was to include under the "building archaeology" label different experiences gained in many research centres and universities disseminated in Italy (Siena, Genova, Venezia, Brescia, Roma, Milano), there are not still shared tools and practices. However, building archaeology is recognised as a functional tool for knowledge and an indispensable guide for a responsible preservation project, despite the different points of view. The building archaeology tools are the building stratigraphic, chrono-typology, archaeometry, dendrochronology, analysis of materials, surface finishes, and construction techniques, together with non-destructive diagnostic investigations (Mannoni 1994; Boato, 2000; Boato, 2008). Building stratigraphy is the tool borrowed from archaeology that helps to understand the elevations to interpret the construction phases. It is based on the "Sus", representing a part of a building that likely was built together, resulting from a single constructive action. Thus, it is necessary to know the historical building site's construction techniques and processes, specifically related to the building's cultural and geographical context (Doglioni, 1997). However, the life of a building is also marked by other processes of adding (positive SU) or removing (negative SU) parts to repair damages or meet new needs. SUs can also be divided into surfacing (wall masonry) and covering units (finishing). Studying the unit borders and the "contact points" between one SU and another becomes essential to understand the relationship and reconstruct the chronological sequence. In this phase, the study of mortar joints is a fundamental step in exposed masonry façades.

4.2. The main façade of the church of St. Francesco

The façade's building archaeology has been one of the first steps for the church's preliminary analysis. The main façade of the Church of St. Francesco is representative of the church's long history of construction, extensions, and renovations carried out following various events, including earthquakes, such as the last that struck Arquata del Tronto in 2016. The building archaeology analysis has presented diverse challenges, partially due to the typical uncertainties linked to the lack of documentary materials supporting the study and partially to the difficulty of reading the façade's wall texture. Some parts of the façade (above the two doors and the quoins) are covered by fibre-reinforced mortar realised to strengthen the wall, together with metal structural elements, aligned to the interior arches and pillars, installed during the 2016 earthquake's safety measures. The church's geometrical survey was carried out in May and June 2019 through a laser scanner and total station. The façade's orthophoto helped to document its current situation. The façade drawing is the result of both TLS and orthophoto restitutions. For the parts of the masonry covered by fibre-reinforced mortar, old photographs were rectified. The fibre-reinforced mortar was an obstacle in studying the facade's materials and texture, together with the fact that it was not possible to observe the stratigraphical relationship among the units since the mortar joints are repointed. For this reason, the building archaeology was based on the identification of different stratigraphic masonry units (named after numbers) depending on the type of texture (type, size, shape, and arrangement of the stones), trying to understand the wall-structural continuities, making only assumptions for what concerns the chronological relationship between the identified SUs. Fig. 9 shows the SUs and their relations.

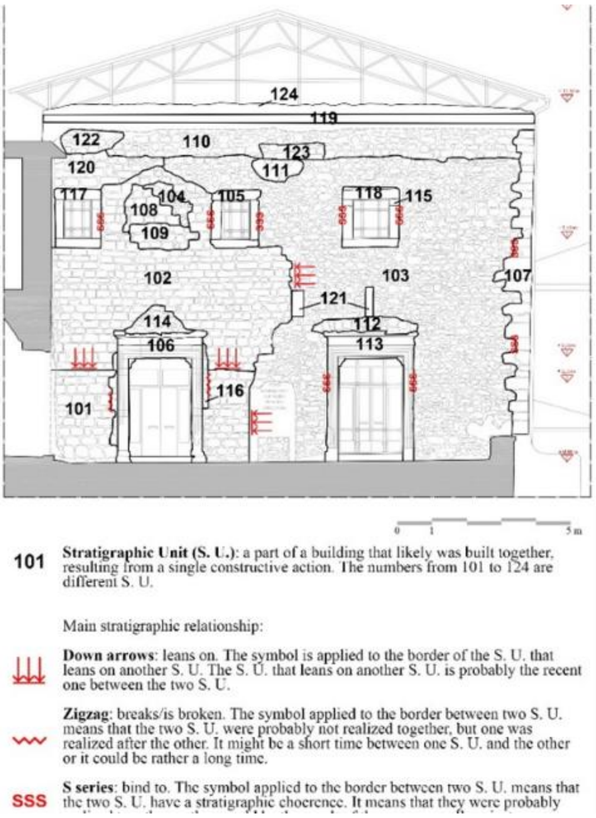
However, the analysis yet opened questions about the church's construction site, history and techniques, materials finishing, and artisans' skills. Even observing the façade in its current state, it is possible to distinguish two types of wall texture: ashlar masonry (101 and 102) and rubble masonry (103). The ashlar masonry is visible on the northern side of the façade and is built of stones with the same height within each course, but each course varies in height. The wall masonry unit 101 has sandstones, whereas the 102 has travertine stones. The stones were probably cut in various forms and dimensions in the quarry, then they were brought to the construction site, and the master builders selected them according to the height to have homogeneous ashlar courses. That is why the stone height range varies from 14 to 30 cm, but stones in each course have the same height. The 103 is a rubble wall with both sandstones and travertine stones. From the on-site inspection, it was possible to notice that 103 leans on the 101 and 102, which means that it was built after them. The same is for 102, which leans on 101. According to bibliographical sources, the church was built around the 13th-century and enlarged in the 16th century (a second nave was added). A wall type similar to 101 (coursed ashlar of sandstone) is visible on the northern side of the east facade (opposite to the main facade, the apse), which suggests that probably 101 is the masonry unit belonging to the 13th-century construction phase of the church. On the east facade, it is possible to notice that sandstones cover a surface that recalls a gable facade. The same happens on the main façade: the top part of 102 is similar to a gable, partially broken by the windows. It is interesting to notice that sandstone was used for the bottom part of the main façade, whereas travertine for the top (Fig. 10).

On the east facade, the wall, probably corresponding to the old side, is made of sandstones. Why do they use travertine over sandstone for the main facade? A possible explanation is that travertine was used at some point to restore the façade, but it is not the main element of the wall. During the inspection of the façade's interior surface, it was possible to see that it seems made of two walls faced with square stone (travertine) and fill *muratura a sacco* (rubble masonry: wall faced with ashlar masonry with an inner backfill of mortarless

Figure 9: The drawing of St. Francesco are the results of both laser scanning and orthophoto restitution: a) the plan of the church; b) the main façade; and c) the cross-section up the aisle.

rubble and dirt). The travertine probably is the exterior facing wall, which could explain why level beds are not aligned on the door's two sides. The rubble masonry, together with sandstone and travertine stone walls, is a

(a) (b) (c)



(d)

Figure 10: Building archaeology of St. Francesco main façade: a) Plaster finishing (113); b) Travertine stone (115) in the window frame (118); c) 1589 engraving on the southern door lintel (113); and d) SU of the main façade and its main stratigraphic relations.

common construction technique in the Sabina region, which is closed to Arquata (De Meo, 2006). Even the level beds of 101 are not aligned on the two sides of the door and seem curving downward, reaching 103. This misalignment could result from the damages that occurred to the old church, probably due to an earthquake. Following this event, presumably, the church was enlarged around the 16th century with a rubble stone wall (103). It could also be that the church's overall structural stability benefits from the addition of the second nave. 103 unit has approximately level beds, brought at intervals to continuous level courses corresponding approximately to every three or four quoins. Quoins have larger dimensions on the bottom of the facade and become smaller, reaching the top. Probably, when they enlarged the church around the 16th century, the old church's quoins (corresponding to the larger ones) were reused for building the newer angle.

The assumption is supported by the fact that the more prominent quoins reach the old church's gable roof level, while other smaller size stones were reused for the top part of the façade. The stone framing of the doors is slightly different. They are made of a lintel, jambs, and two stones above the lintel with brackets (*northern* door), while the *southern* doors have one stone between the lintel and the right jamb. The southern door's brackets are more refined than the northern ones, with flowers and volute engravings. The northern-door frame was probably realised after the southern one, using the same type of stones and technique but with simple brackets. The observation is in accordance with the fact that the 101-masonry wall is broken by the norther'-door frame (106). The southern door's lintel has the engraving "1589" and the door seem to be bound to the 103-wall masonry unit. The engraving helps to place the construction phase of the church's enlargement around the 16th century. Both doors show repairing areas on the top of the lintel. The "rectangular-shaped" area (112) of the southern door is made of square travertine stones arranged in a sort of flat arch. The flat arch could be intentionally built during the opening's realisation.

On the other hand, the "triangle-shaped" (114) area on the top of the northern door may correspond to repairing the damage because it shows the shape of a relieving arch. Each window has its SUs, although they have similar lintels and jambs made of sandstones. The 118 window is different because it has two travertine stones (115) under the lintel. Were the travertine stone installed together with the sandstone jambs? Or do they correspond to a repair? It seems that the 118 window is bound to the 103, like the 'southern' jamb of the 105 windows. The 'northern' jamb of the 105 window and the 117 window are bound to the 102-masonry unit. A window similar to the 118 is visible on the interior surface of the church's 'northern' side. It corresponds to the wall masonry units 104, 108, and 109 of the façade's exterior surface. Furthermore, on the top of the 103 unit, it is possible to see some travertine stones arranged in a semi-circle (111): a repair of an opening? If yes, which kind of opening? An oculus? Do the windows were realised during the same construction phase? Further analysis should be carried out to understand the stratigraphical relationship between windows and walls and the windows and doors arrangement on the main façade.

Another topic that should be further analysed is stone surface finishing. Some sandstones on the east façade presents finishing made with a particular hammer (*martello a due punte*). On the main facade, stone finishing with a hammer was not detected, but on the sandstone of the 'southern' door and the 'northern' jamb window were visible traces of what seems a possible surface finishing: plaster made of lime and eventually fine aggregate, probably with the addition of grey/yellow pigment. Around the 1930s, a report on the condition of the church by eng. Enrico Lancetti expressed the lack of maintenance.

Restoration works took place in 1934, among which the installation of reinforced concrete beams (119) all over the walls. The 110 unit was used to repair parts of the façade, such as the one near the reinforced concrete beam. It is a squared rubble wall, probably reusing square and rough stones from the previous construction sites by placing them following approximately level beds. The building archaeology of the façade has pointed out many questions about the church's construction phases, building site, construction techniques and materials, artisans' skills, and expertise. Many questions remain pending based on the current state of knowledge, but focused inspections could be shed further light on those aspects.

4.3. 3D SUs information and DB extraction

The information derived from building archaeology was embedded in the HBIM. The analysis was carried out to distinguish different types of masonry, depending on the type of texture (type, size, shape, and arrangement of the stones). Since the façade has repointed mortar joints, it was difficult to understand the different SUs' relationship. Thus, some units were grouped into macro-areas, represented by a different colour in Fig. 11.

The macro-areas (corresponding to the colour) are:

- Coursed ashlar (101), probably belonging to the first arrangement of the church;
- Coursed ashlar (102), which probably belongs to the same construction phases of the windows n. 105, 117 and 118;
- Coursed ashlar (120) that has the same texture features of 101;
- Coursed rubble (103), which belongs to the enlargement of the church around the 16th century;
- Random rubble (104, 114), probable belongings to repairs;
- Random rubble (108, 111, 112), probable belongings to repairs;
- Squared rubble (109, 110, 116, 122, 123, 124), probable belongings to repairs;
- Door and windows frames (105, 106, 113, 115, 117, 118), which seem made of the same type of sandstones, but that were probably realised in different construction phases;
- Quoin (107), belonging to the enlargement of the church, probably made by the reuse of stones of the old church;
- Reinforced concrete beam (119), placed in the 1930s restoration phase;
- Mortar (121), which cover the footprints of the medieval reliefs that were removed in the 1980s.

Each SU in the HBIM has its information and related data, such as the description of the wall texture, texture layout drawing, picture, direct and indirect sources. The 'direct and indirect sources' boxes are meant to show where the observation of building archaeology analysis comes from and their reliability. The 3D model embeds even the issues that remain pending or the hypothesis, thus it is a critical tool to study the building. For example, in the State Archive of Ascoli Piceno, it was found the document attesting the realisation of the reinforced concrete beam (119) on the top of the church's walls. Thus it is reliable indirect information.

On the other hand, we do not know if the three windows (105, 115, 118) were realised in the same construction phase: we only noticed that the stones of unit 102 are not broken around the lintel, sill, and jambs of the windows, so they were likely realised together with 102 wall. However, this is just an assumption based on our observation and building archaeology analysis. By distinguishing the sources, even in the HBIM, we try to share the acquired data transparently.

5. Building archaeology and 3D volume stratigraphy: HBIM object decomposition for material analysis

The process of creating the church HBIM required the definition of a generative process able to identify the main architectural and structural elements as well as elements capable of representing the material analysis in a detailed and precise way. In this context, in recent years, various researchers have identified methods capable of graphically identifying material investigations, and thematic areas within the digital model (Altun & Akcamete, 2019; Costantino et al., 2021; Diara & Rinaudo, 2019; Chiabrando et al., 2017, Simeone et al., 2019; Adam et al., 2011). In this context, the value of the

(a)

SU	DESCRIPTION	DIRECT SOURCES	INDIRECT SOURCES	MAIN STRAT. REL.
101	**Coursed ashlar** masonry built of sandstones having the same height within each course, but each course varying in height.	• Thin joints mortar construction, flat-joint repointing. • Level beds are not aligned on the two sides of the door. • Stones dimension (height): from 14 cm		101 is broken by 116; 102 leans on 101; 103 leans on 101
119	Reinforced concrete **beam**	• The reinforced concrete beam was placed to strenghten the roof and the walls during the 1930s restoration.	• Archive document: ASAP, Prefettura, Culto, II versamento, b. 25.	124 leans on 119; 119 leans on 110

(b)

Figure 11: (a) Material and wall texture analysis of St. Francesco main façade; (b) example of the material and wall texture database.

complexity and uniqueness of the elements that make up historic buildings and the subsequent semantic subdivision of objects not present in the BIM libraries (created for new buildings) has conducted various researches to propose alternative solutions to the classic two-dimensional (2D) CAD representations (Cogima et al., 2019; Dore et al., 2015, Li et al., 2014; Massari, 2018; Mol et al., 2020; Nieto et al., 2019; Oriel & Clare, 2015; Pan & Zhang, 2021; Quattrini et al., 2017). The correlation of information to the BIM took place through the creation of 'components' capable of following a pre-set semantic subdivision, where the descriptions of the materials and the subsequent processes were linked to each thematic area. On the other hand, the church of St. Francesco required the implementation of these analyses, going beyond the long procedures for identifying and generating these thematic areas in the HBIM, trying to exponentially reduce the generative phase that still requires the transformation of thematic areas in geometric primitives (splines, polylines, and descriptive tables). In this specific context, for the most part, the material analysis and thematic areas are created using software applications such as Autodesk Autocad, which allows the integrated use of the point cloud, orthoimages and orthophoto in a georeferenced environment. Thanks to the integration of these primary data sources, experts create drawings such as plans, elevations and sections capable of communicating material analyses by simplifying the review of previously identified areas. The main benefits of these 2D representation techniques are many: from the graphic identification of areas on drawings that can support the restoration of the building to the sharing of descriptions and restoration actions to different experts involved in the building's life cycle. Consequently, as briefly mentioned, this traditional procedure still requires long procedures of manual redrawing and the creation of tables and analyses which for the most part are produced separately from the 2D representations through tables and schedules, shared in turn via Microsoft Excel, Word and PDF files. Inevitably, this process is fragmented and processed by several people in multiple digital environments, the latter not being able to communicate with each other. Besides, a further aspect to underline is the total absence of tools capable of mapping with materials that are in turn extractable and numerically quantifiable as occurs in the main BIM applications. For all these reasons, this study demonstrates how the graphic representation process of these material analyses must make use of methods and tools capable of promoting the transmissibility of information in a single shared environment, where the concepts of semantic decomposition, 3D mapping, and computing are enucleated in a single platform, avoiding process fragmentation and loss of information over time. The proposed method makes use of previous studies that have made it possible to go beyond the simple 2D representation or the BIM representation through components. Thanks to the application of Scan-to-HBIM requirements, known as the grades of generation (GOG) 9-10, it was possible to propose a method capable of maintaining high levels of bidirectionality between the semantic decomposition in granular-HBIM objects and the related information (Banfi, 2020). From an operational point of view, the process required non-uniform rational basis-splines (NURBS) modelling and the integrated application of GOG 9 and 10:

Identification and representation of the various thematic areas using different output files of the digital survey such as orthophoto and point clouds in a 3D environment. Thanks to the simultaneous visualisation of the point cloud and a textured model corresponding to the general façade of the church, the surfaces corresponding to the areas of interest were extracted (semantic decomposition) (Fig. 12).

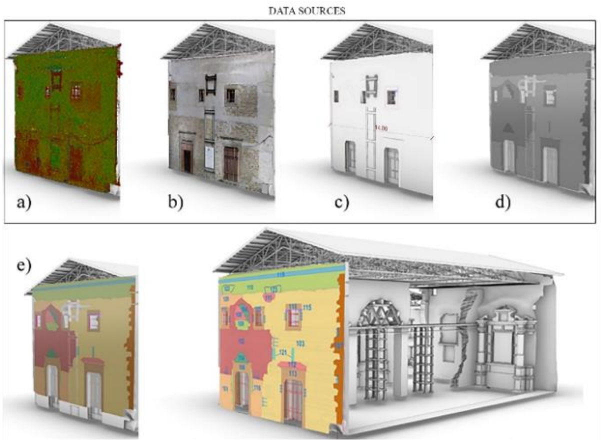


Figure 12: 3D volume stratigraphy extracted from the NURBS: thanks to GOG9 and GOG10 : a) point clouds; b) textured model, c) NURBS surfaces; d) extraction of 3D primitives; and e) 3D volume stratigraphy.

The automatic recognition of NURBS surfaces in the BIM environment. The research objective of this second step was the creation of BIM areas capable in turn of being computed and mapped with descriptions and materials. As is well known, one of the main advantages of BIM applications is the bidirectional relationship between object and information. Once the object was created, it was possible to expand its information value by identifying and creating HBIM parameters. The parameters in turn can be automatically extracted and transformed into databases and schedules capable of correlating a large amount of information and internal/external files to objects. Intending to achieve this internal functionality of the BIM platform, the scan-to-HBIM parameters identified in GOG 10 allowed the transformation of NURBS surfaces into granular HBIM objects (thematic objects corresponding to the material analysis) (Fig. 13).

In particular, the exchange format used to improve the level of interoperability between NURBS applications (McNeel Rhinoceros 7) and BIM software (Autodesk Revit 2021) was the DWG format. At this stage of export, it was found that the simple transformation of NURBS surfaces into a CAD file was not enough. Thanks to a previous study, it was possible to identify the export scheme necessary to allow surface recognition and automatic transformation in the BIM environment. Finally, the correct export of the previously created surfaces made it possible to enter the BIM environment using the mas command.

Application of GOG 10 for the automatic transformation of NURBS surfaces into HBIM objects for the material and decay analysis. Once the NURBS surfaces were imported into the BIM environment, it was possible to automatically transform them into HBIM objects thanks to the wall-by-face command. The creation of these granular HBIM objects consequently allowed 3D texture mapping, the definition of new parameters and the creation of schedules and BIM databases. In this step, it is important to underline the added values of this method unlike previous methods or the use of internal commands in the BIM software created for the management of new buildings. Thanks to the application of GOG 10 (transformation of a surface from a point cloud into a BIM object) it was possible to create a full-fledged stratigraphic volume. The process allowed users to identify not only the irregular wall thickness but also a volumetric decomposition in BIM objects (3D volume stratigraphy). Consequently, the association of the material characteristics allowed the extraction of volumetric values automatically, unlike the simple 2D graphic representation. The added value of this method was found in being able to associate new types of information and allow the creation of parametric objects corresponding to updatable thematic objects corresponding to the material analysis. In this way, unlike simple 3D graphical representations, it is possible to identify wall portions and update their volumes based on subsequent studies and analyses. The volumetric representation and the subsequent transformation into a parametric object implies the transfer from a static 3D representation to a dynamic mode capable of communicating values that are not only numerical such as the materials, their characteristics and the historical phases identified.

Figure 13 shows the expanded information system of the church's façade and how all the identified values are closely related to each other. It should also be noted the importance of declaring the reliability of the model and the grade of accuracy (GOA), level of geometry (LOG) and scales achieved for this type of 3D analysis (Banfi, 2020). At this specific point of the process, BIM parameters were developed to declare the geometrical reliability (quality check) of the various BIM objects with respect to reality (Brumana et al., 2021). The values identified are the following: scale 1:50 with a GOA 50 for the HBIM model, scale 1:20 with a GOA 20 for the decomposition into sub-elements of the main façade (Fig. 14). The following figure shows the GOA achieved for the façade model.3D volume stratigraphy in the BIM environment depending on the level of knowledge and the analysis purposes. The building archaeology mapping helped study the main stratigraphic relationships between the different SU of the main façade and shed light on the construction technique. The 3D representation of the analysis carried out through the building archaeology highlights cognitive uncertainties.

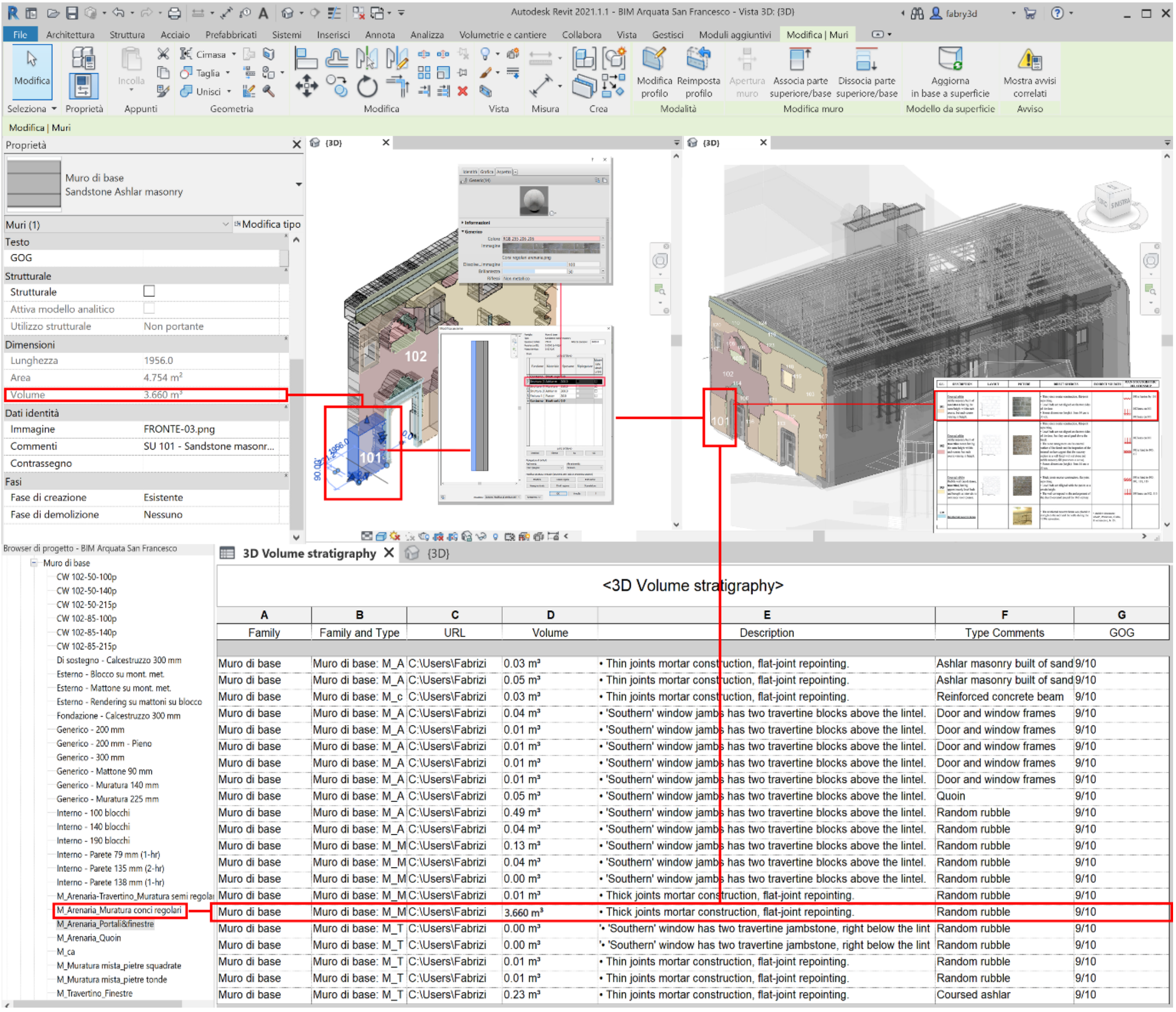


Figure 13: The church HBIM linked to the 3D volume stratigraphy (BIM objects and database).

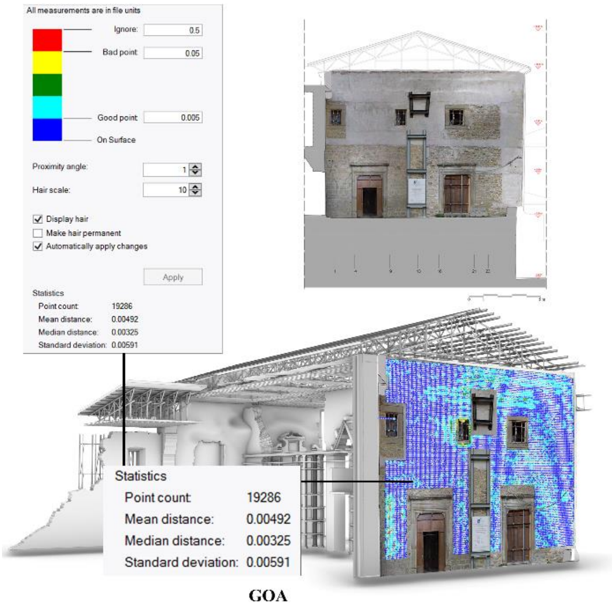


Figure 14: The GOA achieved for the 3D volume stratigraphy within Autodesk Revit.

When the SUs of the 2D drawings “are transformed” into HBIM objects, along with geometrical data, two aspects are particularly significant: i) material and constructive techniques; iii) chronological data. The 3D model leads one to consider how the wall is built and the relationship between its layers (plaster, masonry). Moreover, each HBIM object embeds proprieties and data (i.e. geometries, shapes, areas, volume, construction techniques, chronological and historical information).

The analysis becomes complicated when considering a historic building, whose materials and construction technique is not always easy to understand and may require further investigation, such as non-destructive or semi-destructive testing. Furthermore, the material analysis goes along with the decay mapping, which opens other issues: the decay is related to the material or stratigraphic unit or involves different areas of the façade? The 3D volume stratigraphy was carried out on three representations, but they do not correspond to three different levels of detail (from the less to the more detailed) (Fig. 15). The three representations can be considered as different hypotheses and different uses of the 3D model.

They helped manage the uncertainties on different grades following the granularisation of the model. Case 1 represents the façade made of wall-BIM objects according to the SUs; Case 2 represents the facade made of wall-BIM objects according to the wall layers; Case 3 represents the facade made of BIM objects for each element of the wall layer (i.e., the stones of the ashlar masonry). The granularisation of the model could follow the needs of a hypothetical restoration intervention, which requires the elements to be differentiated according to material and decay analysis or bill of quantities. Moreover, 3D volume stratigraphy is a critical tool to interpret the building component relationship, construction phases and “structural discontinuities”.

- **Case 1:** Each SU comprises different layers (from the exterior to the interior: SU – ashlar stone masonry, rubble masonry, ashlar stone masonry, plaster, and a baseboard). Case 1 gives a first wall structure, which could later be detailed with the various layers. It is a method that could be used when the layers of the wall are not known. Case 1 is not suitable when different construction phases are identified in the wall layers. For example, since SU 101 is one BIM-wall object with its layers (SU, rubble masonry, ashlar stone masonry, plaster, baseboard), if one assigns to the object a specific construction phase, it means that all the layers chronologically belong to this phase, which may not be true. In the hypothesis that SU 101 and 102 are covering and non-load-bearing structures, they could be built together with the rubble masonry or they may correspond to the following construction phases. "How long after the realisation of the rubble masonry " is another pending question.

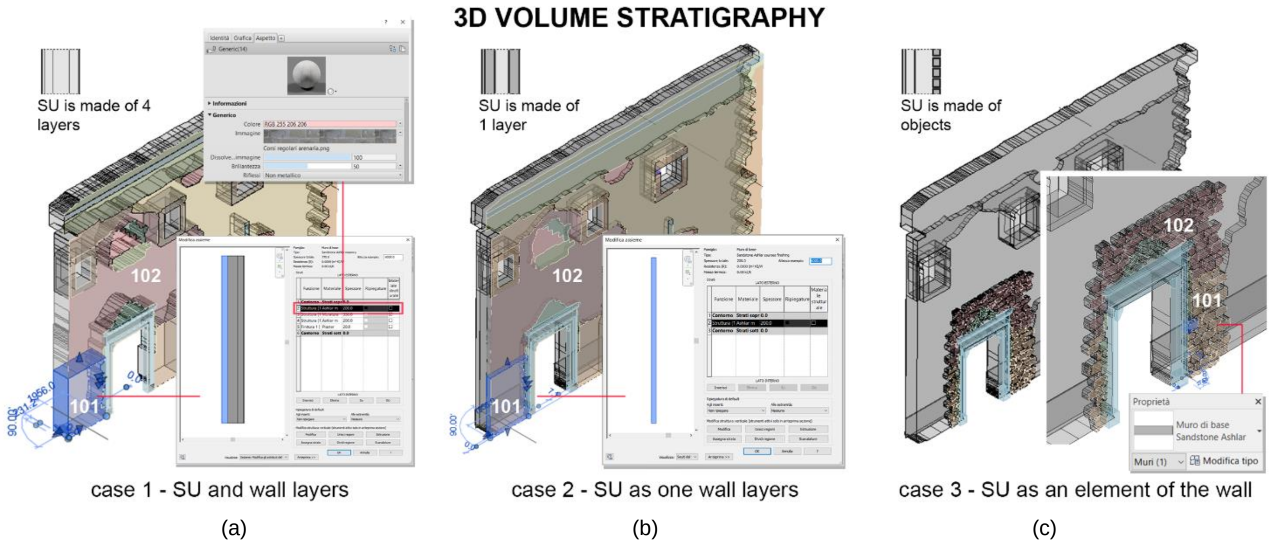


Figure 15: 3D volume stratigraphy in the HBIM environment: a) Case 1 wall structure detailed with various layers (materials are linked to each wall portion and its stratigraphy; b) Case 2 wall structures are composed by proper "consistency" and thickness (each element corresponds to a 3D object with its stratigraphy); and c) Case 3 wall structures are composed by stones that make the SU.

- **Case 2:** Each hypothetical layer of the wall has its proper "consistency" and thickness. In this way, the wall is made of different layers, from the exterior to the interior: SU – ashlar stone masonry, rubble masonry ashlar stone masonry, plaster, baseboard. Case 2 could be used when different SUs belong to the same wall structure or in the case of repairs made of different materials than those of the façade, which thickness is not the same as the façade. Thus, it is possible to represent the hypothesis that the northern part of the façade comprises the rubble masonry as the wall bearing structure, while sandstone (SU 101) and travertine (SU 102) ashlar masonries are a sort of "surface coating". For a hypothetical preservation plan on SU 101 and 102, it could thus be easier to calculate the area and volume of the surface coatings without counting the thickness of the rubble masonry. Moreover, Case 2 allows distinguishing the wall layers according to the chronological phases.
- **Case 3:** Each stone that makes the SU are identified and modelled. This representation could be useful if one wants to characterise each constructive element by adding properties, i.e., when the element is affected by a particular decay. However, the representation of the decay phenomena and process is a separate topic since the decay mapping does not always match the subdivision of the SU. For example, biological colonisation (plant) can concern different materials which belong to different SU. Therefore, in those cases, decay mapping should be represented as an additional layer of the wall, overlapping the ones previously identified, making it easier to be counted in the bill of quantities.

Sharing of analysis and parameters in a cloud-based BIM multi-user environment. The first three steps consequently allowed the authors to enter a computational logic where the 3D mapping took place through the use of specific textures. As is well known, unlike the main NURBS and CAD modellers, BIM applications use textures in which a large number of information and parameters are inserted. In particular, when a BIM object is mapped, it is not only characterised by graphic information but by a large number of material parameters capable of communicating physical, mechanical and historical information of the materials. Thanks to the subsequent creation of schedules within the BIM application, it was possible to export them via the main exchange formats and share them with a large number of experts involved in the church restoration process. To facilitate the reading of this digital architecture, the HBIM and its schedules were shared in a cloud BIM platform capable of displaying a large amount of information via a 3D interface. It should be emphasised that the export of the HBIM project (RVT file extension) in the open IFC format and the subsequent upload of the file to the cloud platform has avoided the loss of the information previously included in the 3D file and favoured the 3D/2D reading of non-expert users of models in BIM. Furthermore, the user can select the BIM object and read all the parameters and information (previously inserted in Autodesk Revit) through a user-friendly interface (Fig. 16). This last phase has allowed authors to move from a digital logic based on proprietary files to an open CDE.

Despite the exponentially expanded information system through these NURBS-BIM-cloud logics, this study also investigated forms of innovative communications capable of using the most modern mixed reality (VR-AR) techniques directly on site. Section 6 will show how all this information has been transferred to different types of users and oriented to different types of devices, with the ultimate goal of promoting an increased and immersive reading of the church directly on site.

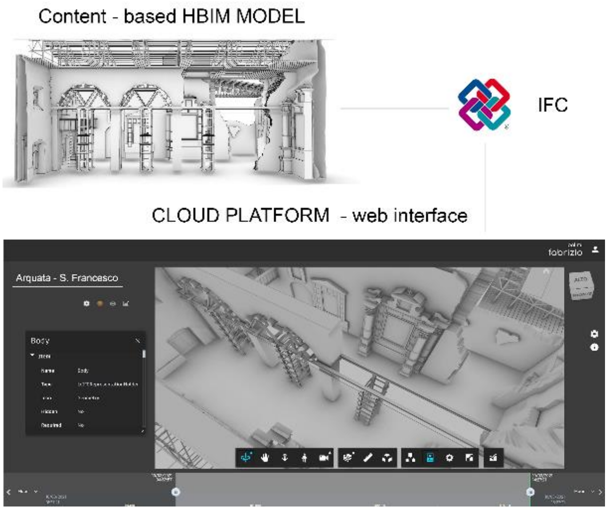


Figure 16: The CDE of the research case study: an open BIM-based platform allows users to display any type of format and analysis.

6. Time-lapse based content model for HBIM and Mixed Reality (VR-AR)

6.1. Franciscan churches and the first arrangement of the church

The data obtained from the on-site analysis are still incomplete today due to the presence of dense scaffolding inside and, partially, outside the church and the impossibility of accessing the convent and its adjacent buildings, belonging to private citizens. However, targeted investigations, albeit incomplete, show a succession of building reforms and enlargements that determine the current state of the church, apparently anomalous: in fact, the church is composed of two naves, the main one ending in a presbytery (with the main altar), and a secondary one, almost symmetrical, ending in a chapel with the altar donated by the Bucciarelli family (one of the most influential families in Arquata). The church built by the Franciscan friars in the 14th century to enlarge that of the first settlement –perhaps owing to the inadequate capacity of the church or earthquake serious damage– is still clearly identifiable today and coincides with a large part of the main nave, in particular with the presbytery, the north wall towards the convent and part of the main facade. This single-nave church corresponds to the results of the typological survey carried out by Bonelli (Bonelli, 1982) and Bartolini Salimbeni (Bartolini Salimbeni, 1993): a large number of surveys and data on the Franciscan churches in central Italy - in particular in the regions of Umbria, Marche and Abruzzi - now allows us to develop comparisons, both in terms of the geometry of the complex, the materials and the employed construction techniques. Excluding the large urban churches, the dimensions are rather small, the length of the nave is between 25 and 50 m, as well as the ratio between width and length of the nave –net of the presbytery– which varies from 1/2.27 to 1/3.82 in contemporary examples (De Angelis d'Ossat, 1982). The Franciscan church of Arquata is fully reflected in its measurements and average dimensions, measuring approximately 25.2 m in length, including the presbytery, and with a width/length ratio of 1/2.41. Moreover, it is the proportion of the nave as compared with the presbytery that is more variable: the latter can have the same width, measure half of it or in some buildings can be even tilted differently. If a rule is still recognisable in the planimetric analysis, the elevations have less intelligible interpretations: the introduction of the choir on the counterfaçade, the wooden ceilings, or the building reforms of the main façade have produced a complex stratigraphy. Further differences can be noticed in the materials and construction techniques employed, largely dependent on the availability of local raw materials suitable for the construction of buildings.

6.2. Church construction phases

The foundation of the Franciscan convent in Arquata dates back to 1251 (Wadding, 1628), about forty years after the passage of St. Francis in this territory. Like most of the early convents, it was a small complex, built in very basic forms. Archival documents do not explicitly mention the presence of a church. However, in 1303, a convent with some tombs was already there (Wadding, 1733). The bell tower, now located in correspondence with the church's north wall, could be part of the ancient convent: the base shows a pseudo-rusticated wall texture, a precious finishing designed to be seen either from the cloister or the churchyard. A portion of the ancient convent could in part correspond with the current sacristy, where sandstone masonry with ogival windows was interrupted and demolished for the erection of the presbytery. Although there is no temporal reference to the construction of the single-nave church, it is possible to date its construction perhaps in the 14th century, also following the discovery of painted finishes after the collapse of 2016.

The church's layout refers back to the numerous examples attested in this area between the 13th and 14th centuries: they can be epitomised in the so-called "*chiesa-fienile*" (hayloft church), with a long nave narrowing into the square-plan presbytery. The proportions used, the presence of antique finishes, wooden corbels and ogive single-lancet windows, the continuity of wall textures prove this typical construction phase (Fig. 17). This church mostly corresponds to the north nave of the current church, into which it was incorporated between the second half of the 15th century and 1655 (Ciociola & Castelli, 2010).

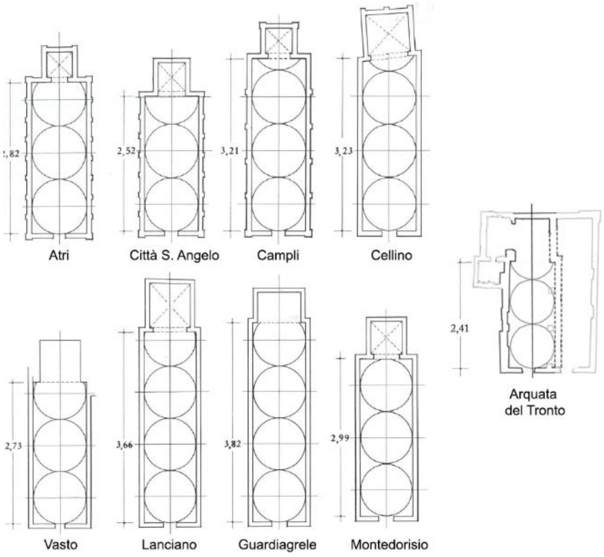
The reasons for this enlargement are unknown: probably an increase in the church's capacity or, more likely, a reconstruction following earthquakes' damage. However the date "1589" on the second main door and the transport of a copy of the Sacra Sindone to the Bucciarelli chapel, in 1655, state two explicit chronological references. The south wall of the Franciscan church was then demolished and the enlargement materials were reused (they are clearly visible towards the Casa Bucciarelli), the two cross vaults in bricks and stones were built above the presbytery and the Bucciarelli chapel, the two naves were equipped with a wooden coffered ceiling, precious wooden altars of local labour were either placed alongside the walls or in replacement of older altars. Until the Napoleonic and post-unification suppression of religious orders, the church continued to be maintained, albeit sparingly, by the Franciscan friars; subsequently, the transformation into a parish and the sale of the convent to private citizens determined an inevitable structural decay. In 1934, following frequent damage and collapses, the roof was replaced entirely, and a reinforced concrete edge beam was introduced along the entire top perimeter of the walls. Restoration and consolidation interventions were necessary following World War II bombings and earthquakes damage (in particular that of 1979); however, the earthquakes of 2016 and the heavy snow loads of 2017 caused the almost total collapse of the roof and the loss of a large part of the historical and artistic heritage preserved in the church.

6.3. The XR project and the virtual-visual storytelling (VVS) of St. Francesco church

In recent years, thanks to the integration of innovative tools and methods such as virtual reality (VR) and augmented reality (AR), it has been possible to go beyond the simple 2D and 3D representation of heritage buildings (Gironacci, 2020; Ioannides et al., 2017, Jang et al., 2021; Jung et al., 2021, Loaiza et al., 2020: Trunfio et al., 2021; Tucci et al., 2019). As anticipated in Section 5, this study proposes an additional solution to disseminating the tangible and intangible values of the church of St. Francesco. The scientific approach for the definition of VVS of the church was based on the identification of different types of digital sources and a large amount of information collected during the historical and cultural analyses of the village of Arquata. In addition to these data, there was the need to tell expert users and not the tragedy of the earthquake and how the latter upset the structure of the building. Consequently, the church's mixed reality project was based on the development of distinct and interrelated operational phases. In Banfi 2020, the necessary operational steps were identified to obtain an appropriate creation of a VVS composed in turn of a large amount of interactive virtual objects (IVO) and information. Scan-to-HBIM-to-VR specifications identified in this previous study made it possible to expand the information value of the HBIM and increase the level of interactivity and its use at the same time. In particular, in Fig. 18, the main phases of the process adopted in the church of St. Francesco have been reported and related with the main objective of remotely telling the historical and cultural heritage of the building.

Unlike previous research, the in-depth analyses carried out directly on-site and integrated into the HBIM gave the possibility to manage the time factor. Thanks to identifying two chronological phases, it was possible to create 3D dynamic views within a single HBIM project and subsequently show them through a time-lapse of the church in the VR project. In particular, through an open development logic, (supported by the Unreal Engine platform), it was possible to create a library of VR objects corresponding to the two phases and

(a)



(b)

subsequently associate them with specific visual scriptings. The flexibility of this computer language, also known as BluePrints, has made it possible to create an interactive simulation of the historical phases of the church. From an operational point of view, the related digitisation took place in two different environments: the first in Autodesk Revit, thanks to the creation of granular HBIM objects, it was possible to distinguish them from each other using the phasing command and create new and personal ones, the second, in Unregal Engine, thanks to the development of a blueprint it was possible to transfer the VR objects corresponding to the two phases and associate them with functions capable of responding to user input. In this particular phase, it was

(c)

Figure 17: a) Internal view of the church after the earthquake - Source: © ing. Romeo Mariani; b) The numerous examples attested in this area between the 13th and 14th centuries concerning the layout of the church; c) the St. Francesco church: aerial view before and after the earthquake - Source: © ing. Romeo Mariani.

useful to deepen the digital proxemics between user and information object. The latter is understood as the study of the distances between two objects, in this case, IVOs and users. Once usable devices such as a desktop personal computer (PC), laptop, tablet, and mobile phone have been considered, schemes have been identified that can improve the discovery of information, recalling the IVOs functions and avoiding misalignments, incorrect visual perceptions and so on. Consequently, the correct distance between user and object allowed to immerse oneself in VR and take advantage of a large quantity of IVOs such as virtual rooms full of information panels, videos, descriptions, reproductions of works of art, historical documents, historical relics (such as the shroud), the creation of 'talking' walls able to show you in-depth material analyses and the related historical phases.

In particular, AR allows you to superimpose data and multimedia information such as text, images, movies from life or in animation to what you are watching on any type of device. As is well known, the camera reads the object in the frame, the system recognises it and activates a new level of communication that overlaps and integrates perfectly with reality, enhancing the amount of detailed data concerning that object.

Thanks to these new technological opportunities, AR has become a useful tool for increasing the information value of different types of objects. Furthermore, different fields of application of the architecture, engineering and construction (AEC) sector have obtained interesting

Figure 18: The XR project developed for the St. Francesco church: theVVS allows users to discover tangible and intangible values of the building through IVO and VR-time lapse for multiple devices.

results in the use and integration of this technology, passing from a pure use aimed at 'entertainment' to a more methodological and scientific use aimed at increasing the informative value, known as 'infotainment'. Given the proven opportunities this technology offers in the sectors of heritage documentation, geomatics, architectural representation and restoration, this study has investigated computer development languages intending to integrate AR in the restoration and analysis process of St. Francesco church.

As anticipated, AR uses the displays of mobile devices and to benefit from additional information. Thanks to the camera, the real environment shown on the display is enriched with animated content, perfectly integrated into the context. Specifically, the technological scenario of AR enables wide and numerous application horizons by showing on the screen both the exterior and the interior of the selected object, videos that explain the functioning of specific architectural and structural components, the dynamics of processes and specificities of materials used. Other significant studies have led to the creation of AR projects able to tell the tangible and intangible values of the building considered by the study. For all these reasons, the development of an AR environment for the St. Francesco church envisaged specific codes of IT implementation (Fig. 19).

Figure 19: The AR project developed for the St. Francesco church: the VVS allows users to discover tangible and intangible values of the building through IVO and VR-time lapse.

As already seen for the VR project, we opted for a digital solution capable of guaranteeing a continuous process of information and data. Thanks to the flexibility of Unreal Engine it was possible to migrate the richness of the VR project into the template dedicated to AR development. IVOs and VVS have been transformed and selected for the semantic enrichment of the new project. Blueprints were decisive for an appropriate IT development that led to the creation of an AR project capable of recalling the material analysis of the façade and its historical information. As shown in Fig. 16, it was possible to observe reality and analyse and deepen a large architectural element through the use of tablets and mobile phones at the same time.

7. Results and discussion

This research has shown how it is possible to go beyond the classic 2D representations through an interdisciplinary methodological approach and undertake a path of digitisation of the built heritage using the latest generation tools and techniques. In particular, the scan-to-BIM process and the 3D survey made it possible to lay the appropriate foundations for a further implementation phase which included new forms of digital sharing. In particular, the need to represent specific information relating to historic buildings has required the development of new HBIM parameters capable of collecting material and historical analyses. Building archaeology was developed considering the benefits brought by GOG 9 and 10 which allowed advanced modelling of complex objects and subsequent semantic decomposition into HBIM objects. The bidirectional relationship between information and object has been implemented to increase the interactivity of the model, facilitating the information mapping and sharing phases at the same time. Through different tests, three volumetric representations in a BIM environment were investigated and proposed with the aim of demonstrating how an earthquake-struck historic building can be digitised even in geometric elements that do not correspond to architectural and structural elements. The concept of 'granular object' anticipated in Banfi (2020), was further investigated to orient the informative model to the preliminary design of the preservation plan of the St. Francesco church in Arquata del Tronto. The digital workflow has made it possible to share with the municipalities and professionals involved in the process a large amount of digital data such as survey data, vector drawings, unique parametric objects, schedules and databases. A cloud-based BIM platform was developed and used to improve communication levels to facilitate this sharing. On the other hand, the process still involves the use of a large number of tools, formats and software. If not mastered with awareness, the latter can lead to an exponential dispersion of information and the consequent loss of the high level of detail and accuracy that historic buildings require.

Furthermore, the development of a cloud platform has not allowed to greatly increase the level of interactivity, immersion and digital proxemics compared to the paid solutions already on the market. The main advantage found was the sharing in open logic (via IFC format) of a large amount of data and a web interface capable of sharing 3D and non-3D geometric data. For this reason, a further phase of development has made it possible to propose new forms of XR to non-expert users, recalling the research addresses anticipated by the call Horizon 2020-2021. In this context, an XR project was developed mainly to tell the tangible and intangible values of the case study, creating an immersive environment able to tell the historical and cultural background. Throughout IT development and visual scripting, it was possible to tell through VVS the tragedy that hit the hamlet of Arquata and its inhabitants, tracing and archiving testimonies that could be lost over the years. Similarly, the digital twin has been developed to improve the interoperability between the HBIM model and the virtual model of the church characterised by a large number of IVO where the non-expert user can easily interact and discover step by step, click by click, the contents collected by the integrated digitisation process. The future challenge will include developments aimed at further simplifying the integration of these data (digital-born) and their sharing (tablet and mobile phone versions still have evident limits from the point of view of the size of the models), starting from the survey up to more advanced forms of virtual sharing. In this context, the survey of buildings and structures affected by seismic damages presents several challenges from a safety point of view and considering proper planning of the acquisition that may be hindered due to clutter, scaffolding, and temporary structures. For those reasons, future works will follow two different typologies of analysis: the definition of automated and/or remotely piloted systems and the implementation of detection and filtering strategies to identify clutter in the point cloud. Indeed, the development of an automated and remotely piloted system may allow fast and safe acquisition of the primary data besides the possibility to control the system allows adjusting the planned path remotely. On the other hand, the possibility to identify and filter unwanted elements and clutter in a point cloud may speed up the modelling phase by reducing the amount of data, while preserving the relevant features.

However, little literature focuses on the specific application of neural networks for the classification of point clouds acquired in a post-seismic context. In conclusion, the proposed research method poses undoubted advantages for the analysis of the factory, for the verification of the succession of the construction phases and therefore for the understanding of the construction techniques and the consequent structural behaviour and failure mechanisms. Especially in a building that can only be detected for parts, mostly damaged or hidden by scaffolding and strengthening measures. The limit of HBIM consists of the extreme precision of the output, which does not admit doubts or uncertainties. For example, in the core of the walls, it is not always possible to identify exactly boundaries or construction techniques or clear geometries between the units; the analysis in St. Francesco church did not allow to comprehend the geometry and construction techniques of the foundations or, for example, in the main façade, the connection between the inner pilaster and the façade, composed of different construction phases. In summary, the results obtained should not be considered a certain point, an outcome, but rather as part of a process that is always open to other investigations that can be continuously updated or implemented.

8. Conclusions

In recent years, the daily practices of experts involved in the preservation of the heritage building process have benefited from innovative tools and systems capable of improving ultra-detailed analyses and digital representations. On the other hand, technological developments require the definition of scientific methods capable of enhancing and improving their use in specific fields of application and disciplines such as restoration, geomatics and architectural representation. For this reason, this study proposes a method capable of going beyond ultra-detailed HBIM projects. In particular, the case study of the church of St. Francesco in Arquata after the 2016 earthquake made it possible to develop a research methodology capable of increasing both the quality of the output-files and analyses produced in 3D environments and the level of communication among all experts involved in the preservation process of the building. In this context, the application of specific GOG (9 and 10), the development of specific HBIM parameters related to 3D volumetric stratigraphic analysis, and the use of a CDE allow users to improve the level of communication of intangible values of the surveyed artefact. The 3D volume stratigraphy has been a tool for the restorers to draw the preservation plan, going further to the 2D representation of building archaeology. It helps us show the stratigraphic relation on the façade surfaces and understand how each unit interacts in 3D, on the elements' depth. The 3D stratigraphic model is a critical tool and a way to convey the façade materials and construction techniques (a starting point for the preservation plan) and even to manage uncertain aspects that the building archaeology analysis raised up and the pending issues that still need further inspections. The information on each SU is available in the database regarding direct and indirect sources (i.e. if they derive from on-site observation or archival documents), documenting the provenance of the collected data.

This study shows the results obtained in the field of XR, developing a project able to interactively tell the history of the church and share a large amount of analyzed and studied data. Furthermore, thanks to IVO, it was possible to go beyond the use of static models such as meshes, NURBS, and HBIM projects. Thanks to specific computer languages, the user through specific inputs can interact with a large number of levels, videos, interviews, informative panels, descriptions and objects capable of coming to life. Finally, the case study of the main façade of the church has laid the foundations for undertaking a more augmented architectural representation than analyses on 2D forms. To support the 3D volumetric analysis directly on-site, an AR project was developed that can communicate specific descriptive fields in favour of a 360° immersive material analysis.

Acknowledgements

The authors thank the Municipality of Arquata del Tronto (RUP Mauro Fiori and arch. Davide Olivieri). Preliminary Restoration Design, Scientific Responsible Manager: A. Grimoldi and A. G. Landi. Collaborators: E. Facchi, E. Zamperini (POLIMI DAStU).

The work presented in this paper has been partially supported by the research: “Study on quality in 3D digitisation of tangible cultural heritage: mapping parameters, formats, standards, benchmarks, methodologies, and guidelines” VIGIE 2020/654: coordinator CUT Cyprus, ERA Chair and UNESCO Chair.

Thanks to the graduate students Andrea Rusconi and Luca Rovelli for the VR content implementation. Thanks to the SSBAP students (POLIMI) for the stratigraphic analysis, 2019 workshop, prof. R. Brumana, A. Grimoldi, and F. Doglioni.

Credits: Scientific responsible: R. Brumana; Surveying and scan-to-BIM process: F. Banfi, R. Brumana, A. G. Landi, M. Previtali, F. Roncoroni, C. Stanga; Laser scanning: M. Previtali, F. Roncoroni; HBIM and XR projects, 2D drawings, building archaeology: F. Banfi, R. Brumana, A. G. Landi, C. Stanga, M. Petrone (POLIMI DABC, Lab. GIcarus).

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