Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): surveying, preservation, site intervention—the Basilica di Collemaggio (L'Aquila)

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Abstract

In December 2012, EniServizi (the Italian multinational energy company), after the Earthquake that occurred at L'Aquila in April 2009, decided to undertake the project "Re-start from Collemaggio", funding around 14 million Euro to restore the Basilica di Collemaggio. EniServizi, aware of the BIM potential role in the complex building and infrastructure domain in the world, required an advanced HBIM based on laser scanner and photogrammetric surveying to address decision-making processes among the different actors involved in the preservation process. The Basilica of Collemaggio has been re-opened to the public on December 2017. This paper tries to make a synthesis of the different lessons learnt, in relation to both positive and critical aspects relating HBIM feasibility, sustainability and usefulness to the challenging restoration and preservation field. The theo-retical and practical HBIM approach here tackled overcomes the current BIM logic based on the sequential process adopted by the AIA and NBS Level of Development (LOD), characterized by a simple-to-complex-detailing process, working in the new construction domain and generally following the conceptualizing phase, the preliminary design, the executive design, the construction phase till to the facility management. A complex-mixed LOD approach, able to entail the richness, unicity and multiplicity of each component and to get the maximum degree of knowledge, has been experimented in order to derive informed decisions in terms of preservation, restoration and management since the starting phases of the architectural design. To this aim, a Level of Geometry (LOG) coherent to the Level of Accuracy gained by the high-resolution surveys has been adapted to the specificity of the restoration process of a historic monument and is here proposed through different Grade of Generation (GOG) protocols developed in the object modelling to support the preliminary and definitive design proposal of the conservation plan of the Basilica. Particularly, a NURBS-based parametric generative modelling process (GOG9-10) is here proposed in order to get models "BIM abled" to describe the complex geometry and to match the related information. Specific Level of Information (LOI) has been introduced to support the preservation process, to document the as-built and the management of the building after the intervention, moving HBIM toward multi-actor domain. Given the effort required by such approach, obtaining a cost-effective HBIM modelling embodying the complexity of each damaged element as acquired by the surveys (i.e. walls, pillars, vaults, beams) represents a challenging issue. The result of the overall process aims to contribute in lowering the initial HBIM modelling costs by deploying a sustainable complexity delivering protocols and specification and by boosting at the same time an interop-erable cooperative HBIM habit among multi-actors across all the phases, spreading its usability after the restoration process. On the lesson learnt, the process of updating the current Codification criteria (UNI11337-2009) has been started with a draft proposal stimulating the debate for the future of HBIM adoption in the case of restoration, preservation and maintenance (UNI11337-2017): in the conviction that transferring the HBIM richness into the Life Cycle Management process will allow multi-actors to take in account the knowledge and information gained during the restoration, integrating the as-built updating and keeping updated the monument monitoring during the time being.

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Introduction

On April 6th, 2009, at 3:32 a.m. an earthquake (Richter Magnitude 5.9) struck L'Aquila (Central Italy): 309 victims, 65,000 displaced people. More than 10 billion Euro of estimated damage, about 100 churches uninhabitable for the major collapses, along with thousands of historic buildings in the old town centres. Among them, the Basilica di Collemaggio was significantly stricken: the dome, the transept and triumphal arches collapsed with their pillars, and great damage occurred to the apses, to the pillars of the arched walls of the nave and to the longitudinal north front with the "Holy Door" (Gattulli et al. 2013).

The Basilica, a world-famous medieval church, is a Romanesque masterpiece characterized by a dense, fascinating history and construction phases, which began in 1270, with many stratified interventions occurred across the centuries. Every year, it attracts about 30,000 people for the Forgiveness Feast Day (Festa della Perdonanza) on 28–29th August. The Forgiveness Feast Day is celebrated with the procession ceremony transferring the original Bull from the Municipality to the Holy Door of the Basilica, as established by Pope Celestino V. The result is an extraordinary unique mix of tangible and intangible values the design and restoration process intends to preserve and transfer to the future.

The restoration project "Ripartire da Collemaggio" (Restart from Collemaggio)[1] has been undertaken and funded by EniServizi with the aim of giving new hope to the L'Aquila community, together with the Superintendence Office of L'Aquila and a large scientific team of universities (Fig. 1).

Starting from a high level of knowledge produced by previous studies on the dynamic behaviour of the Basilica (Antonacci and Beolchini 2004; Antonacci et al. 2001a, b), the challenge was to improve BIM tools, tuning BIM, which is adapted to existing buildings (Volk et al. 2014), toward Built Heritage Conservation-deploying shaping tools (Della Torre 2015): the objective is to obtain HBIM able to combine the complexity of the geometrical shape (Brumana et al. 2017) with the architectural design purposes and preservation aims.

[1] The Superintendence Office carried on the restoration project after the earthquake damages, with the scientific support of the Università degli Studi de L'Aquila, the Università La Sapienza di Roma, under the coordination of the Politecnico di Milano (Scientific Responsible Prof. Stefano Della Torre).

The HBIM has been carried on by integrating laser-scanning geometric surveying[2] (Barazzetti et al. 2015a) and the hand-on survey of the pillar ashlar[3] (Oreni et al. 2014) with the information coming from the historical and archive research[4] and from the diagnostic phase with the material, construction technology and decay analysis[5] carried on by the Conservation Plan.

The Conservation Plan[6] has been developed to answer to the following issues: (a) an architectural design project supporting a decision-making process devoted to the preservation aims, (b) the management of critical issues regarding the need to preserve authenticity of materials and construction techniques, and (c) the need to guarantee safety in case of other earthquakes with higher energy dissipation with respect to the last that occurred, or at least equal to it.

Given the main aim, which was to preserve the maximum level of material authenticity, functional behaviour and construction techniques, HBIM generation of the Basilica needed to take into account the whole complex monument with all the structural components relating one to the others, considered as the result of the ancient construction phases and of the transformations that occurred across the centuries, including the earthquake effects and damages.

HBIM managing the paradigm of complexity: LOD, LOG, LOA, and GOG protocols

It is nowadays recognized by different researches carried out in the last years that BIM can take a role in a holistic organization of models and information, needing to define a

[2] The geometric surveying and HBIM have been carried out by the Politecnico di Milano (Prof. R. Brumana), geomatics research team (R. Brumana, L. Barazzetti, F. Roncoroni, M. Previtali, F. Banfi, B. Cuca)—ABClab GIcarus http://www.gicarus.polimi.it, feeding and defining LOD-LOG-LOA and GOGs as des2cribed.

[3] The pillar ashlars surveying, interpretation and HBIM data integration have been carried out by Daniela Oreni, together with the plan and section interpretation (Politecnico di Milano), feeding the LOG F and G proposal.

[4] The historical research has been carried out by the research team of the Università La Sapienza Roma (Prof. G. Carbonara).

[5] The analysis of materials, decay and construction technologies have been carried on by Lorenzo Cantini (Politecnico di Milano) defining and feeding the HBIM LOI F&G as described.

[6] The Conservation Plan has been carried out under the coordination of Politecnico di Milano (Prof. S. Della Torre).

Fig. 1 Photographic sequence showing (**a**) the area stricken by the 6th April 2009 earthquake and the damages occurred to the Basilica and (**b**) the provisional covering realized after the seismic event and the opening of the Holy Door during the Jubilee Forgiveness procession

framework for the HBIM, considering the "specific" case of documentation of architectural heritage (Fai and Sydor 2013; Oreni et al. 2013) and its preservation (Megahed 2015). Given that the preservation process requires a deeper level of knowledge since the starting phase of the design (Della Torre 2015), BIM adoption requires to be turned to the preservation aims, restoration and management process (Della Torre 2016; Della Torre 2017), developing coherent models whose accuracy matches the complexity of the architectural heritage (Brumana et al. 2017).

In fact, the traditional concept of the Level of Development (LOD) applied to the BIM management in the case of new construction is based on a linear process progressively enriching both the model and the information across the different phases (even if with different accent on the letter "D" of the LOD acronym concept intended as Level of "Development", (AEC 2014; AIA 2015), and as Level of "Detail", (NBS 2016)): LOD100 represents a conceptual a-dimensional model, LOD 300 a three-dimensional model in the executive design phase, LOD350-400 represents the model implemented for the construction phase and LOD500 the as-built updating after the construction phase. This distinction is oriented to manage all the information useful for the maintenance process of the building in the time, including the layer stratigraphy of each element category.

Such linear approach progressively detailing the BIM (model and data), on the geometric and information side, till to the texturing information and stratigraphic layer sequences, cannot be automatically applied to the restoration–preservation management process: it risks to delay the knowledge of the geometry, the state of the art and behaviour of the structures with high cost increasing during the process due to unexpected framework. In addition, lack of information limits the possibility to undertake design solutions coherent with the state of the art and the preservation actions.

The method here proposed intends to apply a Mixed and Reversed LOD approach, based on accurate 3D surveys feeding the HBIM in the architectural design phases: as a consequence, the Level of Geometry (LOG) and the Level of Information (LOI)–articulating the LOD concept–need to be further defined in order to match the preservation aims as described in the "IntroductionS15" section.

Having clarified "why", the problem is to identify "how" an accurate LOG can be implemented since the starting preliminary design phase to support a robust decision making within a technical and economic sustainable framework. If the three-dimensional model characterizing the LOD300 has been applied to the design simulation solutions, as in the case of the crashed dome area, to be further detailed as in the new construction BIM praxis, the concept of the LOD500 richness needed to be anticipated to detect the damaged structures. LOD500 is, in fact, characterized by a detailed level of geometry enriched by stratigraphic data (model) and texturing (information) here required before the management phase respect to the new construction.

Here, we assume to deploy the Level of Geometry–generally adopted in the LOD500–for the Level of Development of the design phase (LOD300). Maybe in the future being it will need to be better specified in the Codification Criteria. For now, it seems more important to remark the needing of developing and adopting a generative modelling coherent with the complex geometries of the monument from the design phases.

Here, a high-resolution Level of Geometry has been generated, enriched by 3D arrangement texturing and by the information on the stratigraphic layers (materials, decay, chronological phasing).

For this matter of fact, the concept of GOG (Grade of Generation) protocols has been introduced in order to describe different Levels of Geometry, in function of the geometry detected by the cloud scans, particularly for the damaged walls, gaining a morphological accuracy of the model coherent with the surveyed surfaces of the walls, enriching such models with the arrangements (as in the case of the pillar-ashlars and of the brick-block vaulted systems) since the starting phases of knowledge and design; a deeper Level of Information on materials, construction technologies and decay analysis has been deployed to be matched to the models.

Scan-to-BIM generative modelling: LOG and GOG protocols

The surveys of the Basilica have been carried out to properly check the whole damage in the Basilica (Barazzetti et al. 2015a), including the punctual out of plumbs of the vertical elements (Fig. 2), walls, arched walls and pillars, and the geometry of the damaged vaulted systems, to support the knowledge of state-of-the-art, the structural analysis and the preservation plan.

To this aim, a geodetic network has been carried out to strengthen the cloud scans co-registration acquired by Faro Focus3D© laser scanner (obtained accuracy: $\sigma = \pm 3$ mm) and the 3D photogrammetric image block processing covering all the vertical wall surfaces and the vaulted system getting a robust survey with a high level of accuracy (Table 1). A first draft release of the drawings on the base of the survey (plans and vertical sections) was delivered (May 2013) starting from the on-site campaigns. A first HBIM drafted version was delivered at the end of 2013 in support of the preliminary steps of the design project and the definitive-executive steps (2014–15). The pre-condition in the case of Collemaggio was the reliability of the HBIM model accuracy of each element of the Basilica under the geometric point of view and under their interopera-bility to be linked and related to the different information, and to be managed by the different actors, including for structural analysis (Barazzetti et al. 2015b). As a consequence, the HBIM has been addressed to manage the geometric richness and morphology acquired by the laser scanner point clouds.

The definition of the novel concept of "Grade of Generation" (GOG 1–10) and Grade of Information (GOI), related to the object modelling, allows the operators to adapt the logic of the traditional LOD sequence (100–500) defined by the AIA specifications (2010–2017), to the specific case of architectural heritage restoration, introducing as part of the process the method and functionalities adopted to generate the model objects themselves. Starting from the cloud scans, a procedure has been developed to generate the object models within the CAD environment and/or within other specific modelling software (such as MC Nell Rhinoceros ©), implementing new GOG protocols to manage them within the BIM tools, as fully operational BIM object elements.

Particularly, methods capable of processing Non-Uniform Rational Basis-Splines (NURBS) to describe the richness and unicity of each element have been experimented with prom-ising results: a novel parametric modelling approach based on a highly accurate survey has been deployed to manage the gained richness within BIM tools (Banfi 2016). A complex parametric BIM modelling has been obtained introducing dif-ferent Grades of Generation (GoGs) able to take in account the different levels of simplification and complexity coherent with the Level of Accuracy (LOA) got by the survey, in function of the objectives and in function of the geometric characteristics (Scaioni et al. 2013).

The GOG sequence ranges from GOG1 to GOG10 (Table 1): GOGs 1–8 define integrated simplified functionalities (i.e. based on extrusion, subtraction and other modelling function-alities) adopted for portions of walls where the standard devi-ation with respect to the cloud points is contained in the order of 1–2 cm; the complex sequences of GOG9 and GOG10 (scans to NURBS-based object surfaces) have been intro-duced (Banfi 2017) to get a Level of Accuracy of the model with respect to the point cloud contained in the order of 2–4 mm for the damaged structures (i.e. walls with out of plumbs ranging from 0 to 24 cm, the arched walls and pillars with the out of plumb

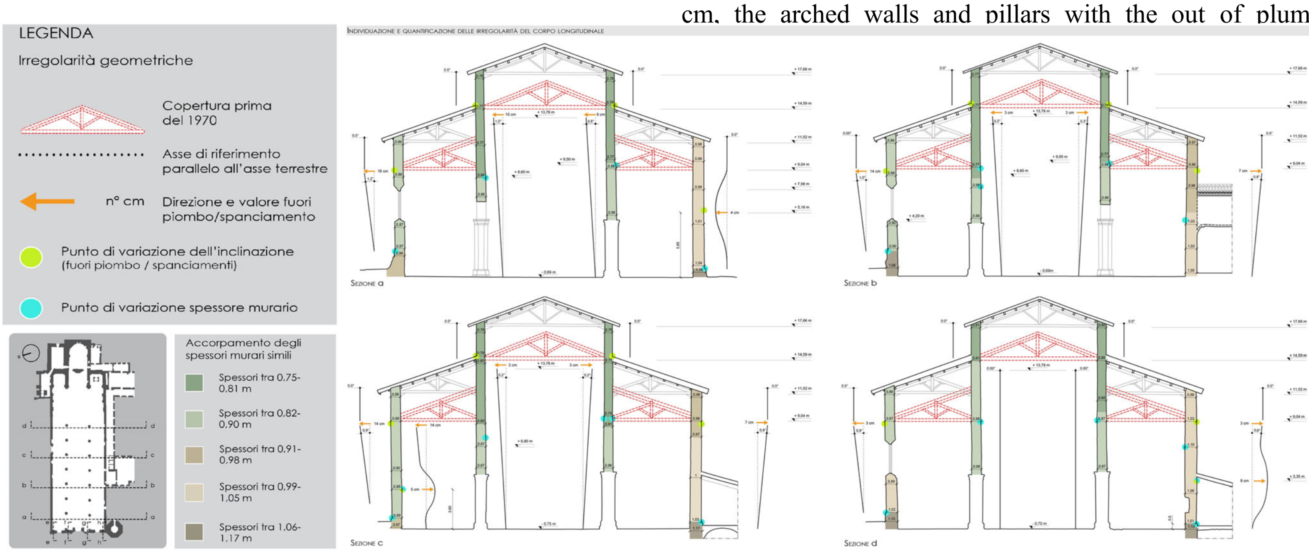


Fig. 2 The vertical sections of the Basilica highlighting the complex geometry of the damaged walls, punctually represented with the different out of plumbs and thickness ranges obtained from the scans

Table 1 Surveying accuracy, level of geometry, level of model accuracy: activities, dimensions, efforts

On site surveying accuracy & HBIM LOD-LOG modelling		Personnel effort/quantity	Effort/quantity/precision	Effort accuracy (LOD & LOG & LOA)
On-site surveying campaigns	4 days × 5 persons (1st campaign) (expert surveyors: 3 Eng. 2 Arch.)	3 days × 5 persons (2nd campaign) (expert surveyors: 3 Eng. 2 Arch.)	2 days × 3 persons (3rd campaign—data validation)	TOT ~ 40 days (320 h)
Survey	Geodetic network	27 stations	$\sigma = \pm 1$ mm	
	Total station points (cloud co-registration and GCP image blocks)	260 points	$\sigma = \pm 1.5$ mm	
	Laser scanner FARO Focus 3D	182 point clouds	$\sigma = \pm 3$ mm	
	Hands on ashlar-pillar	n. 14 pillars, n. 574 ashlars (9–13 courses each pillar)	TOT ~ 53 m^3	
	3D photogrammetry	Surveyed surface area	TOT ~ 7.000 m^2	
Horizontal plans	Plan	All plans (including underground level, crypt and 1st floor)	TOT ~ 4200 m^2	
Elevations	3D orthophotos	External and internal fronts; vaults (intrados)	TOT ~ 7000 m^2	
Detailed HBIM model of the Basilica di Collemaggio: damaged structures: apses, altars, bell tower, transept, naves, crypt, cloister, corridors, crypt, underground vaulted basement.	HBIM elements: walls and openings (external walls, arched internal walls), pillars (pillars-ashlars), arches, vaulted systems, roof, timbers.	I. HBIM development without GOG approach (2013–2015)–n.1 BIM expert modeller–600 h (BIM modelling) + 200 h (pre-operational procedures) + 120 days not skilled workers (n.3 M.Sc. thesis students starting from zero BIM skills). II. HBIM development adopting GOGs (2017 new generative HBIM modelling)–1 BIM expert modeller 300 h (BIM modelling) + 120 h (pre-operational procedures)	Volume of the Basilica covered by the HBIM: TOT ~ 50,000 m^3 HBIM object-volume generation TOT ~ 14,000 m^3	LOD500 richness adopted since LOD300 (design phase) Level of Geometry characterized by GOGs 1–10 related to standard deviation of the cloud for each HBIM element: LOGs & GOGs models maintain surveying accuracy (cloud points): GOGs 1–8: *Simplified model object* adopted for vertical walls with non-planarity or out of plumb ≤ 20 mm. GOGs 9–10: *NURBS-based model object* adopted for elements with standard deviation respect to the conceptual simplified solid ≥ 20 mm. NURBS-based object is modelled obtaining a final standard deviation respect to the cloud points ≤ 2–4 mm
Simplified HBIM model Collemaggio	Simplified volumes: provisional safety structures, design scenario simulation (cover and crashed dome solutions), building-adjacencies not interested by the design proposal and intervention (i.e. cloister)	500 h × n.1 medium skilled modeller		LOD300

GOG9 and GOG10 have been introduced to shape the complexity of objects such as irregular walls, pillars and vaults (Fig. 3). Particularly, vertical walls with a standard deviation with respect to the cloud planarity check ≥ 20 mm or with out of plumb ≥ 20 mm; pillars or vault elements with a standard deviation with respect to the generative concep-tual solids ≥ 20 mm. A multi-slice based wireframe model (GOG9) and/or cloud-based model (GOG10) have been adopted for each 3D parametric object maintaining the mor-phologic richness and precision acquired by the survey. The generative process has been deployed to boost the HBIM management in case of complex shapes, defining new pro-tocols made by different sequences of procedures (Banfi 2016), enhancing the LOD richness adopted by the execu-tive design typical of LOD300 (Fai and Rafeiro 2014; Banfi et al. 2017) to the LOD500 richness.

Particularly the option GOG9–NURBS-based complex modelling (border and slicing) defines protocols for object modelling based on outline/border extraction (3D Edge inte-grated by inner slicing from the cloud scans); the option GOG10-NURBS-cloud-based (borders and clouds) defines protocols based on outline/border extraction (3D Edge) inte-grated by cloud points, thus obtaining to enrich the surface morphology lowering time of slicing.

Moreover, the 2 GOGs, have been implemented in order to support the mathematical parameterization and the informa-tion managing within the BIM environment (as Revit© or others). The method has an immediate result in obtaining a fully operational BIM object of the modelled complex ele-ments. This procedure avoids the generation of the most com-mon used “components” generally modelled for complex morphologic elements (i.e. inside Revit©) that cannot be linked to the information, being not fully parametric compo-nent objects.

The proposed BIM modelling procedure can be separated in different phases of the process (Fig. 3).

Particularly:

- Modelling phase 1 (geometric primitive determination) is relative to cloud pre-processing and extraction of the edge border by the point clouds of each object to be modelled;
- Modelling phase 2 (object modelling, GOG1–10) is rela-tive to the modelling phase in function of the survey re-sults and of the geometric morphology, the required model accuracy and the level of development.

Particularly, NURBS-based GOG modelling sequences (9–10) may be carried out within advanced common user friendly modelling software (i.e. MC Nell Rhinoceros©) and exported to be parameterized and managed as parametric object within BIM tools, thus automatically generating area and volume dimensioning. Being parameterized, they can be related to the different information, differently from the mass object or components (phase 4).

Level of Geometry (LOG) GOG 1–8: simplified solid model objects adopted for elements which conceptual model has a standard deviation respect to the cloud points ≤ 20 mm (i.e. vertical walls with non-planarity or out of plumb ≤ 20 mm).

Level of Geometry (LOG) GOG 9–10: NURBS based adopted for elements with standard deviation respect to the conceptual simplified solid ≥ 20 mm (i.e. vertical walls with a standard deviation respect to the planarity check ≥ 20 mm, or with out of plumb ≥ 20 mm; pillars, vault elements and other components with a standard deviation with respect to the gen-erative conceptual solids ≥ 20 mm).

- Modelling phase 3 (automatic verification system—AVS) gives back the grade of the level of accuracy of the model object with respect to the surveyed clouds, highlighting the deviation of the point cloud respect to the modelled object in the different GOGs undertaken, with the final result ≤ 2 mm.
- Modelling phase 4 (BIM generation): parameterization of the GOG models within the BIM tools; such object can be finally related at the end of the process to different LOIs.

Based on the assumption that historical buildings are made of structural elements such as irregular walls, pillars, vaults and arches, different one with respect to the others due to the design, realization and transformations that oc-curred, the study describes the generative process capable of creating specific and accurate three-dimensional ele-ments of the medieval basilica, “as-found” after the earth-quake, transformed across the centuries and damaged by the earthquake.

The generative process from the first phase of processing is represented by the creation of accurate 3D parametric objects following the GOG9 and GOG10 generative modelling pro-cess and protocols described previously (Banfi 2017). The method applied to the generative process of the HBIM pro-vided the integration of Non-Uniform Rational Basis-Spline (NURBS) modelling (Piegl and Tiller 1997; Dimitrov and Golparvar-Fard 2014) with the parametric logic of the BIM application. The NURBS model of the basilica is a mathemat-ical representation able to achieve complex three-dimensional architectural and structural objects, transmitting the accuracy level of the data sources (point clouds) collected by laser scan-ning and photogrammetry.

The seismic actions caused damages to the walls, pillars and vaulted elements of the basilica: the BIM object models obtained represented the physical geometry as-found after the earthquake with an accuracy contained in 2 mm between points and modelled objects. It is the case of the NURBS-based BIM modelling of the damaged north front with the

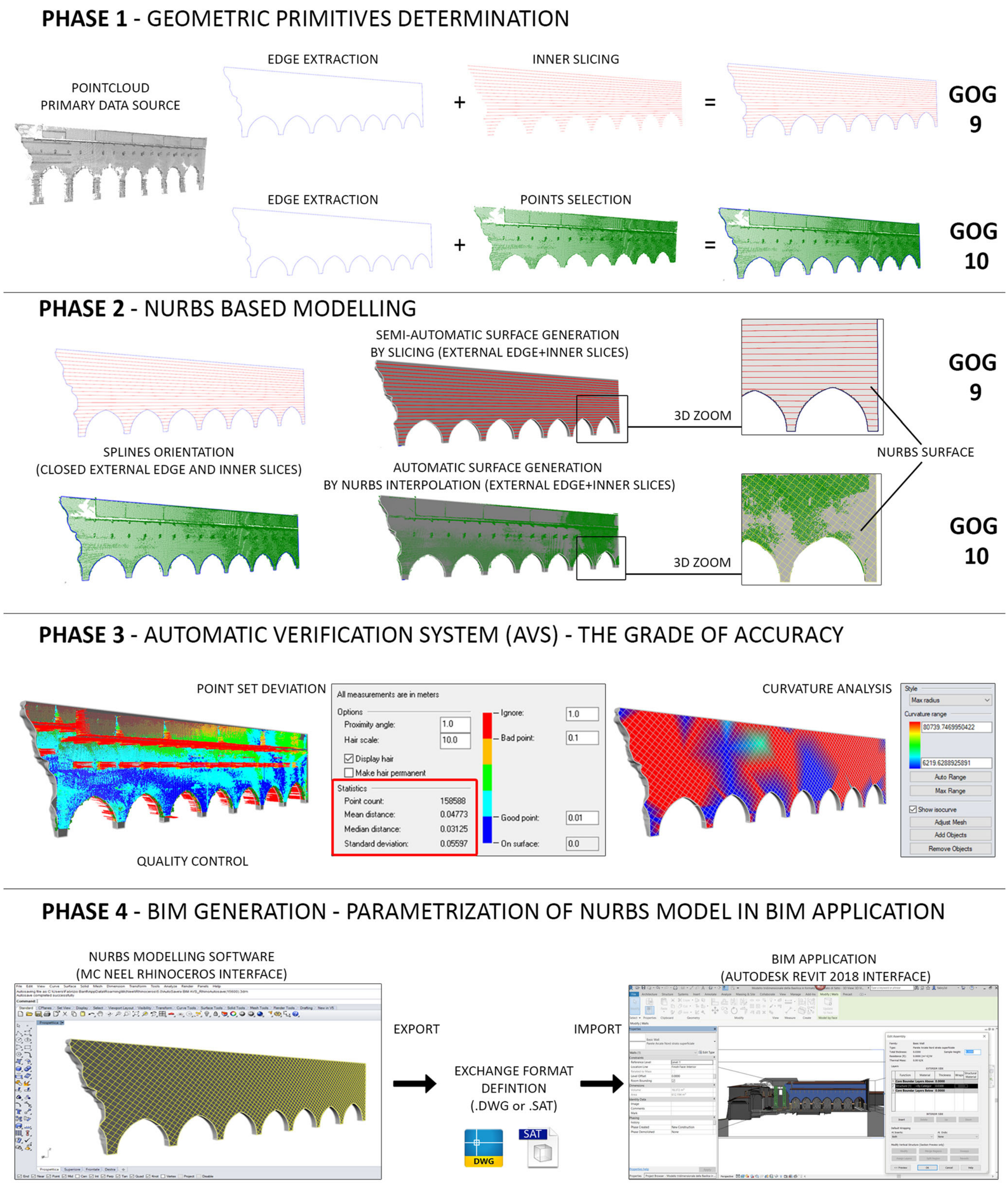


Fig. 3 SCANtoBIM process: the case of GOG9 and GOG10 generative complex modelling (the arched wall of the nave). The phases from the point clouds to BIM object generation: Phase 1: Geometric primitives determination. Phase 2: NURBS-based modelling. Phase 3: Automatic Verification System (AVS). The accuracy gained by the model with respect to the points with the point standard deviation related to the model object obtained. The NURBS-based complex modelling adopted for each 3D parametric object maintaining the morphologic richness and precision acquired by the laser scanner point clouds. Phase 4: BIM generation—parameterization of the NURBS model within the BIM tools

Holy Door (Fig. 9, paragraph 4.2), affected by several local effects, changes of plane, vertical settlements, rotation, struc-tural cracks and out of plumbs (0–25 cm). To this aim, the HBIM model was generated from laser scans and integrated by 3D multispectral photogrammetric image processing, in-cluding UAV data (Barazzetti et al. 2014): this made it possi-ble to continue the first assessment, to supporting the diagnos-tic, material and decay analysis, the structural evaluation, and the design process (Fig. 10, paragraph 4.2). In the case of the vaulted systems, the object element parameterized within the BIM environment has been implemented by the construction technology gaining a level of detail enriched by the arrange-ments: such level of detail is useful to improve the understand-ing process during the life cycle management (Brumana et al. 2018).

The study carried out on NURBS and geometric primitives led to improvements in the level of automation and accuracy of each element. Thanks to the combination of various ad-vanced modelling techniques and the proper use of generative edges and profiles, the process can be managed as a semi-guided process avoiding long lead times and the relatively high costs involved in the digital 2D/3D representation (Table 2). The generation of proper geometric primitives and the management of the generative digital process led to the creation of transmissible three-dimensional elements. Clustering exchange formats (.dgw, .sat., .stp, .pts) made it possible to obtain and transfer 3D slices, profiles, control edges and complex shapes from a versatile 3D NURBS mod-eller (i.e. MC Neel Rhinoceros ©) to the BIM application (i.e. Autodesk Revit ©).

Level of geometry and level of information: generative model to manage related information

One of the main goal of the HBIM of the Basilica was the improvement of the level of transmissibility of data among different experts such as architects, designer, restorers and structural engineers involved in the 3D survey, structural anal-ysis, design and restoration phases of the Basilica in support of a decision-making process able to reach the objectives of preservation and safety.

The flexibility and scalability of a novel generative method of HBIM for the Basilica of Collemaggio have made it possi-ble, through rigorous 3D modelling, tests and statistic valida-tion, to gain a level of accuracy (LOA) of the Object Models coherent with the surveying LOA, by adopting different GOGs to get the proper Level of Geometry (LOG) taking in account the morphology, as-found after the earthquake, to understand the state-of-the-art and a reliable level of knowledge.

The object elements properly modelled and parameterized as described can be finally related to the different information, qualitative and quantitative, in terms of properties and dimensions (Fig. 4). Each architectural and structural element of the damaged church can be related to a growing Level of Information (LOI) as described in paragraph 4.2. The HBIM of the Basilica was conceived as an interoperable tool to man-age different steps (diagnostic analysis, finite element analy-sis, economic analysis, construction site, cost computation, Work Breakdown Structure, restoration, LCA/LCM), where LOG LOA and LOI can be adopted and implemented during the different phases, without the LOD rigid sequence from simple to complex adopted for the new construction. Particularly for the damaged structures or fragile ones, the LOG is declined by the GOGs 9–10 in order to obtain the most accurate shape to support the following phases. The process allows the operators to avoid simplification, skipping the knowledge of the real state of the art, before the decision-making process.

We could define GOGs as available protocols to develop the LOG with different levels of modelling from the simplified ones (GOGs 1–8) till to the NURBS based ones (GOGs 9–10).

The transmission of the high level of information depends on a proper generation of the modelling phase for the HBIM management of all the object elements and their hierarchical connection (i.e. wall nave, pillars, pillar-ashlars, arches, arches-ashlar), in terms of modelling (morphological aspects) and management of linked data (information and DB coming from the other experts involved, as in the case of historical phases, materials, decays).

The mutual transmission of information during the conser-vation and structural restoration of architectural heritage re-quired high levels of interoperability of exchange formats and the combination of various Advanced Modelling Techniques (AMT) in order to get an accurate three-dimensional paramet-ric model. AMT has solicited research tests with particular emphases on “knowledge” of 3D modelling innovative logics and the development of digital tools. It achieved a generative process with a high level of parameterization (3D Objects/ Editable information), starting from the scanned shapes, and providing a scientific basis to get a reliable level of knowledge to start the architectural planning and make structural engi-neering decisions.

HBIM on-site management: the CASE of the ancient pillars

Numerous challenging decisions have been faced by the in-volved university team experts (restorers, structural engineers, historians) addressing the decision making and the interven-tions, to guarantee the maximum degree of preservation of material authenticity and of the ancient construction techniques.

Table 2 A comparison of the HBIM modelling of some components among the adoption of GOG1–8 and the novel adoption of GOG9–10. It is not computed the pre-operational time and drawing restitution

WALL	INTERNAL SPACE VOLUME m^3	WALL VOLUME m^3	GROSS FLOOR AREA m^2	TIME REQUIRED BIM GENERATION BY GOG 2013 (GOG 9-GOI 1-2) & 2017 (GOG 10-GOI 1-2) (Hours - h)	TIME REQUIRED BIM GENERATION BY TRADITIONAL PROCESS (GOG 9) (Hours- h)	LEVEL OF DETAIL (LOD)	REF. HBIM OBJECTS
MAIN FACADE	/	1274	/	30h, 2013 & 15h, 2017	35-40	300	
TOWER	929	190	LEV.01+02=140	6h, 2013 & 2h ,2017	10-12	300	
NORTH WALL	/	1141	/	20h, 2013 & 3h ,2017	30-35	500	
SOUTH WALL	/	941	/	8h, 2013 & 3h ,2017	12-15	500	
INTERNAL NORTH WALL ARCHES	/	537	/	20h, 2013 & 3h ,2017	12-15	500	
INTERNAL SOUTH WALL ARCHES	/	460	/	15h, 2013 & 6h ,2017	20-25	500	
BELL TOWER	437	180	LEV.01+02=25	20h, 2013 & 15h ,2017	25-30	400	
APSE WALLS	11,491	1790	LEV.01=823	60h, 2013 & 25h ,2017	70-80	500	
APSE VAULTS	/	160-190	/	50h, 2013 & 20h ,2017	60-70	500	
CRYPT	977	250	LEV.00=336 LEV.01=280	60h, 2013 & 20h ,2017	50-60	400	
ROOF	36,987	7,244	LEV.01=2194	120h, 2013 & 50h ,2017	130-140	500	
TOT.	51,000~	14,000~	3798~	409h~, 2013 162h~ ,2017	522~		

The HBIM challenge is to enhance instruments and tools able to take into account the dynamic characteristic of the masonry structure, the fragility of the elements and of the overall system asking for a new equilibrium after the earthquake, as in the case of the nave system: with the arched wall out of plumbs, damaged pillars, the cracked apse, the longitudinal front with Holy Door characterized by relevant out of plumbs and the wooden trusses roof. The BIM from the

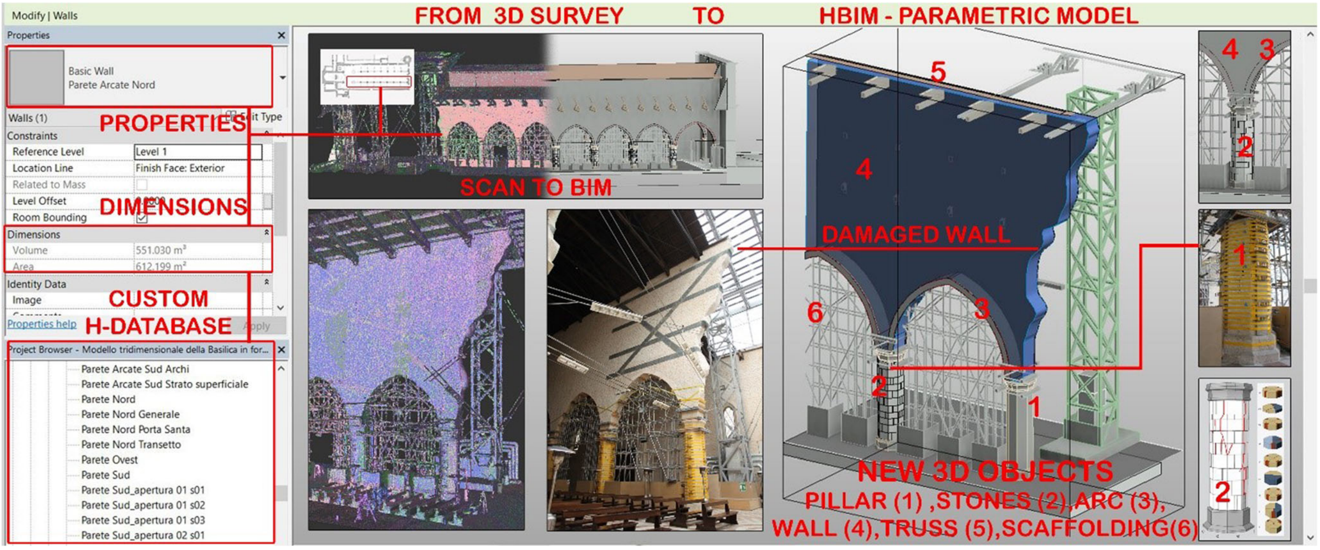


Fig. 4 HBIM parametric modelling and the 3D object management allow relating the different information (such as quantities and dimensions, and qualitative data, as stratigraphic properties, materials and construction technologies)

design phase starts entering in the phase of the on-site intervention.

From the geometrical survey of stone ashlars of the pillars to the HBIM inventory model

Hereafter is considered the case of the BIM of the ancient pillars and the ashlar-LOD obtained to support the preservation of the maximum number of pillars and of the single stones: during the on-site intervention many of them have been saved, maintaining in place the undamaged ashlars as much as possible, and substituting the damaged and crashed ones.

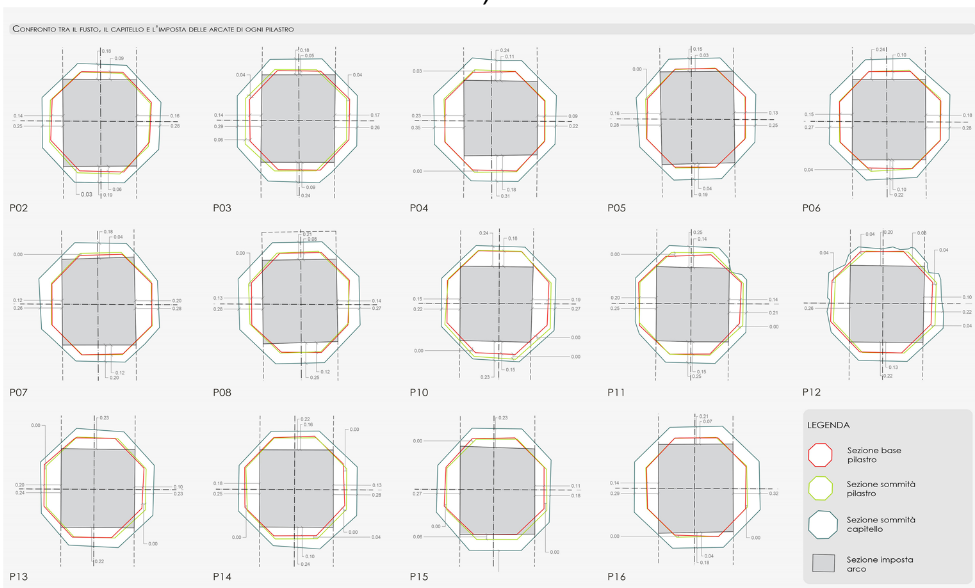
During the diagnostic investigation (2013–2014), the exact geometry of the extrados of the octagonal columns of the nave was derived, to detect the morphology, and the punctual out of plumbs of each pillar, obtained from the laser scans (Fig. 5a, upper); the mosaic composition of the ashlars with their di-mensions and the crack analysis has been carried out integrat-ing an hands-on survey, ashlar by ashlar (Fig. 5b, bottom). Laser scanner and photogrammetric data could not be used to identify ashlar division, because of the dense network of wooden boards on four of the eight faces of the pillars, and because of the provisional horizontal fabric hooping added after the earthquake by the firefighters public body, thus saving the pillars (Oreni et al. 2017). It was therefore essential to proceed with the integration of the hands-on survey of each pillar, in order to draw the shape and disposition of every stone element.

Unfortunately, it was not possible to analyse directly the inner core of the pillars, due to the reduced safety of the structure. Ultrasonic investigation had been performed in a first phase, but these tests did not give a significant response on the nature of the inner core, because of the diffused cracks influencing the velocity of the signals and its distribution maps in the plane sections (Quaresima et al. 2015). The direct assessment shifted at the opening of the yard, thus needing an updating of the hypothesized model of aggregation of the single ashlars.

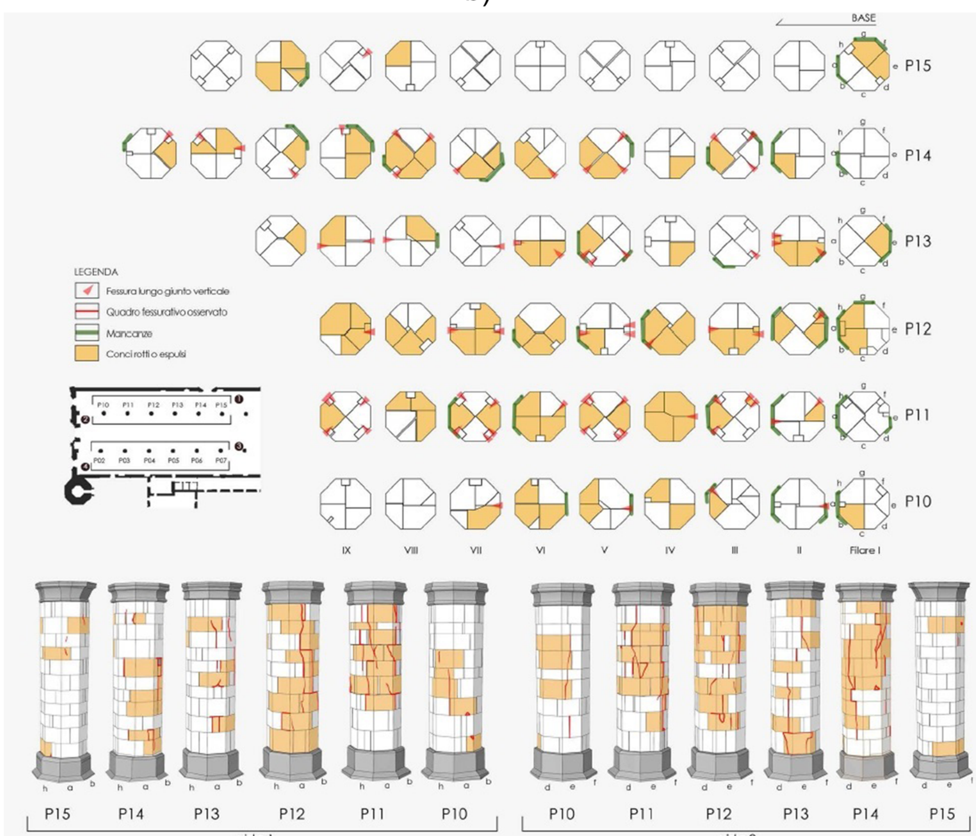
The geometrical and material analysis conducted on the pillars showed also a generalized diffusion of patch elements, characterized only by a hypothesized thickness, presumably variable from one zone to another. The crack pattern and position of the broken or degraded ashlars were mapped in detail, in order to plan the different conservation activities: replacement, integration or consolidation. The damaged ashlars have been highlighted in orange inside the HBIM inventory model. The geometric survey recognition of the ashlars of every pillar was finally drawn with 2D (plan and fronts). It has been hypothesized an average of 35% of ashlars to be necessarily substituted during the intervention, with the consciousness that this percentage would surely have been increased during the works. The analysis of the compressive strengths required a careful choice of the new stones (Quaresima et al. 2015).

Fig. 5 **a** The SCANtoBIM process of the damaged columns: the horizontal scan profiles sliced at different height levels of the courses highlighted the out of plumbs, here represented on the plan (upper). **b** The HBIM inventory model of the pillar ashlars with the 3D model (GOG 9) of each column (left); the hands on survey allowed to implement the BIM with the stone ashlars modelling (right): in yellow, the broken ashlars of all the pillars integrated by the information on the materials, volume, area, and diagnostic analysis and crack analysis. Mapping (LOI): a Level of Detail typical of the LOD500–600 has been derived since the first year of the work to support the definitive design. **c** The HBIM final global model of the octagonal pillars with their stone ashlars related to the other BIM elements, the springing arches of the nave and the GOG10 wall (bottom) ▶

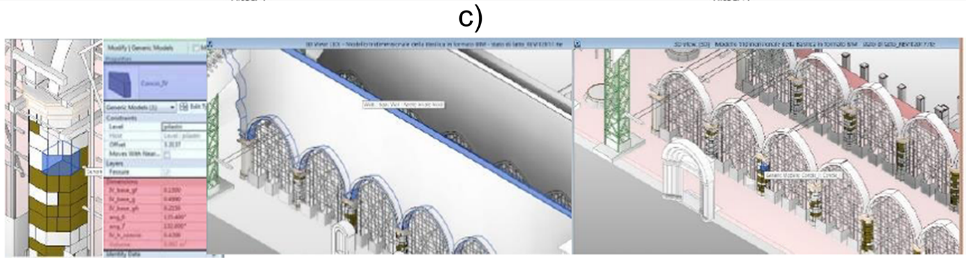
a)


Confronto tra il fusto, il capitello e l'imposta delle arcate di ogni pilastro
P02
P03
P04
P05
P06
P07
P08
P10
P11
P12
P13
P14
P15
P16
LEGENDA
Sezione base pilastro
Sezione sommità pilastro
Sezione sommità capitello
Sezione imposta arco

b)


BASE
P15
P14
P13
P12
P11
P10
LEGENDA
Fessura lungo giunto verticale
Quadro fessurativo osservato
Mancanze
Conci rotti o espulsi
IX
VIII
VII
VI
V
IV
III
II
Filare I

c)



At the end of the punctual generation of the HBIM inventory model, each BIM column (LOD600) has been related to all other object elements (walls, arches and temporary struc-tures), as shown in Fig. 5c.

HBIM inventory model of the pillars: as-found and as-built. The "scuci cuci" conservation activity of the stone ashlars and the disassembling and reassembling activity (about 50% of ashlars saved).

Such careful survey aimed at enabling the control of local repair works, avoiding or minimizing the total dismantle of pillars. In the design phase the decision, taking in account the lack of information on the quality of the inner core, was to disassemble only the most damaged pillars, which are also exposed to the highest actions in case of earthquake.

Two different conservation activities have been planned in the design project on the pillars (Fig. 6, upper left): "scuci cuci" (red) in place conservation on the less damaged pillars with the punctual replacement of the single damaged stone ashlars (Fig. 6b): it was initially planned on the Pillars 10-11-12 and 02-03-04, the ones closed to the façade, and suc-cessively adapted to the effective condition during the resto-ration, sometimes extending the conservation to other pillars; a global disassembly and reassembly of the stone ashlars (blue) realized on the most damaged pillars, the ones closed to the crashed dome (Fig. 6a): in this case, the hypothesis was to substitute the broken damaged ashlars with new ones, maintaining the same external shape and dimensions, as surveyed, but prolonged to substitute all the angle of the central core, therefore strengthening the section anyway. As a consequence of lack of information on the core, it was evident that the number of elements to be completely substituted would have been updated on the restoration site.

It would also be especially necessary to deeply investigate all the areas interested by past restoration interventions, where the old cracks had been covered, in some cases using filling mortars made from the powder of the same stone, hiding any other broken ashlar (Oreni et al. 2017). Similarly, only con-structive suppositions could be made about the size of the mortar internal core of the pillars (visible only in column n. 06, through 2 holes allowing to get the measure thanks to the light crossing over them), definitely variable in position and dimension. Once the column restoration had been started (2016), it was possible to gradually compare the geometric information ascertained from diagnostic external investigation with the support of the HBIM with the information procured from the restoration activities, especially concerning the cen-tral pillars (P04-05-06-12-13-14).

Starting from the upper part, the ashlars of the pillars most stressed by the seismic actions and extremely degraded (Crespi et al. 2016), were disassembled, numbered and reassembled on the floor (Fig. 6). This operation made it pos-sible to verify the exact geometry of the stone elements, to evaluate the material and thickness of the central core (Fig. 6), comparing the state of the art with the HBIM hypothesis, to recognize the broken elements (not visible from the outside) or the one that seemed in a worse condition and to refine and rectify the drawings made during the diagnostic phase (the as-built HBIM is on course of updating). The first phase of the on-site intervention of column restoration consisted in downloading the vertical loads of the arched walls by progres-sively inserting temporary metal structures under the two rel-evant arches in order to carry out the intervention on the pillar. This operation made it possible to continue with the on-site intervention of stone ashlar replacement or completely disassembling and reassembling the ashlar of the octagonal columns.

Gaining all the information gathered by the HBIM integrat-ed by the on-site observation, made it possible to validate the survey method used in the diagnostic phase and the results obtained, both in terms of geometric analysis and of the vol-ume stone to be replaced. The number of the damaged ashlars have been estimated approximately 35% (orange), and at the end of the intervention approximately 35%–50% of the stone volume have been saved. Taking in account that at the begin-ning of the surveying it was hypothesized–among the different options–the complete substitution of the ancient pillars, we consider a good result the saving of the integer ashlars in the disassembled pillars and the conservation of the pillars inter-ested by punctual "scuci cuci". All in all, in fact, a good correspondence was registered between the geometry of the detected blocks and the real ones, albeit with some expected, and in some cases also important, differences. The major dif-ferences are linked to the failed detection of some broken stone elements in the inner part, along with fracture lines not visible from the outside, or covered by temporary wooden structures. As assumed in the diagnostic phase, the substan-tially limited thickness of the patch stone elements, mostly due to restoration work performed by the Superintendent Moretti in the 1970s, was recorded. In fact, the restoration phase gave back a multiplicity of thicknesses. The case of Pillar n.13 shows the case of better ashlar stone conservation with respect to the hypothesized state of the art of the inner before disas-sembly and after reassembly. The external deterioration of the stone, in good condition in the inner part, is evident (Fig. 6a, bottom). Differently to the case of Pillar n. 12, where the disassembly of the central columns of the nave has shown a big difference between the shapes of the core of each row, depending on the stone ashlar dimension and disposition (Oreni et al. 2017).

The central core occupies a variable percentage of the total area. The material filling the core was a kind of "incoherent mortar", weak in the binder and poor in aggregates, similar to the mortar analysed in pillar n. 6 during the diagnostic phase.

Fig. 6 HBIM, "as found" and "as built". The two different conservation activities planned in the design project on the pillars (upper-left): the global disassembly and reassembly of the stone ashlars (blue) with approximately 35–50% of the stone volume saved, realized on the most damaged pillars; and the "scuci cuci" (red) in place conservation on the less damaged pillars with the punctual replacement of the single damaged stone ashlars. **a** Case of Pillar n. 13 (upper)—before disassembly (as-found) and after reassembly (as-built) and the HBIM model. It is shown a Pillar with better ashlar stone conservation with respect to the hypothesized state of the art of the inner. The external deterioration of the stone, in good condition in the inner part, is evident. Comparison of the external surveying of the ashlars and the ashlars after disassembly: row I (HBIM). Top image of a pillar during its disassembly: the irregular mortar core of the column (upper-left). **b** Case of Pillars n. 10 and 11—"Scuci cuci" (bottom): the drawings made during diagnostic phase without inspections and the 3D-HBIM ashlar inventory model (as-found). Comparison of the external ashlars after the earthquake and the ashlars after the "scuci cuci" intervention (as-built)

Throughout the restoration activities, it was possible to recover some stone elements, in some cases using metal connections or paste, which was considered seriously damaged in the diagnostic step; in that case, their external condition did not reflect the inner one. Therefore, it was possible to recover them as in the case shown in the previous figure.

For the pillars in a better state, repair without disassembling has been preferred because this way the conservation of the actual disposition of ashlars has been conserved. The survey enabled to detect significant differences in the position of the joints, which in the pillars of one row are correctly staggered, while in the pillars of the other row are not. This fact, which ended up in different crack patterns after the quake, has not yet been explained, but anyway it deserved to be conserved as much as possible, as a component of the authenticity of the historic building.

At the end of the intervention, it is clear the needing to update the HBIM model for the future management. The

BIM updating has to be undertaken after a punctual check that will be carried out in the next year. The HBIM was very useful to support the conservation aim and to help valuating the state of the art highlighting the evidence and consistency of the stone ashlars, and documenting for the future the level of authenticity preserved through the carried out works.

Maximizing HBIM benefits, lowering costs: boosting interoperability among actors.

HBIM to manage conservation plan, design, WBS, FEA and scenario simulation (LOD300)

The adoption of the HBIM approach had an experimental character, as most of the actors were not yet ready to work on the basis of a digital modelled processes. A platform was supplied by EniServizi with the purpose to support an advanced project management, based on advanced digitisation, which was a real achievement in comparison with the customary attitudes for conservation works in Italy, but this Common Data Environment was not yet used as a fully remotely accessible interoperable cloud environment to allow the use of Building Information Modelling in the of investigation, design, procurement, execution, monitoring and maintenance phases.

The HBIM generative model was conceived to support operators, architects, structural engineers, and their activities, economic computation, construction site management, thus allowing to be used within the diagnostic analysis, the design, the construction tender and the restoration itself (2014–2017). The adopted approach allows the HBIM to be updated and adapted by the different BIM actors in order to support the different phase purposes as summarized in the Fig. 7. A sort of live BIM has been achieved adapted to the different actor purposes:

a. Design simulations allowing the comparison and impact assessment of the simulation scenario of different solutions for decisions making about the crashed dome (Fig. 8);

b. Conservation Plan of the overall restoration design (under the coordination of Prof. S. Della Torre), including, within the HBIM, the diagnostic analysis (material analysis, surface decay analysis and preservation project), as described hereafter;

c. FEA (finite Element Analysis) in support of the structural analysis (Prof. A. Franchi and others engineers of the coordination team), addressing the intervention on the damaged pillars, the walls and vaulted system;

d. the Work Breakdown Structure (WBS) of the restoration activities and the computational phase;

e. COnstruction Site Management (Co.Si.M) carried out on the HBIM adding machinery, construction site structures, simulation of the scaffoldings to manage the construction site and to simulate partitions to make the Basilica partially usable during the last phases of restoration (prof. A. Trani);

f. VR/Cloud liveBIM management within Virtual Reality by I-devices for on-site and touristic purposes.

During the Scan to HBIM process, different LODs (Level of Detail) have been defined and adopted in function of the different activities:

- HBIM Conservation Plan: 3Dcomplex Model of the damaged Basilica LOD500;
- HBIM Design project and scenario simulation LOD300 (i.e. solutions on the crashed dome and pillars);
- HBIM Construction Site MGT (CO.Si.M): it needed a simplification of the Level of Geometry from LOD500 to LOD300 (complex to simple);

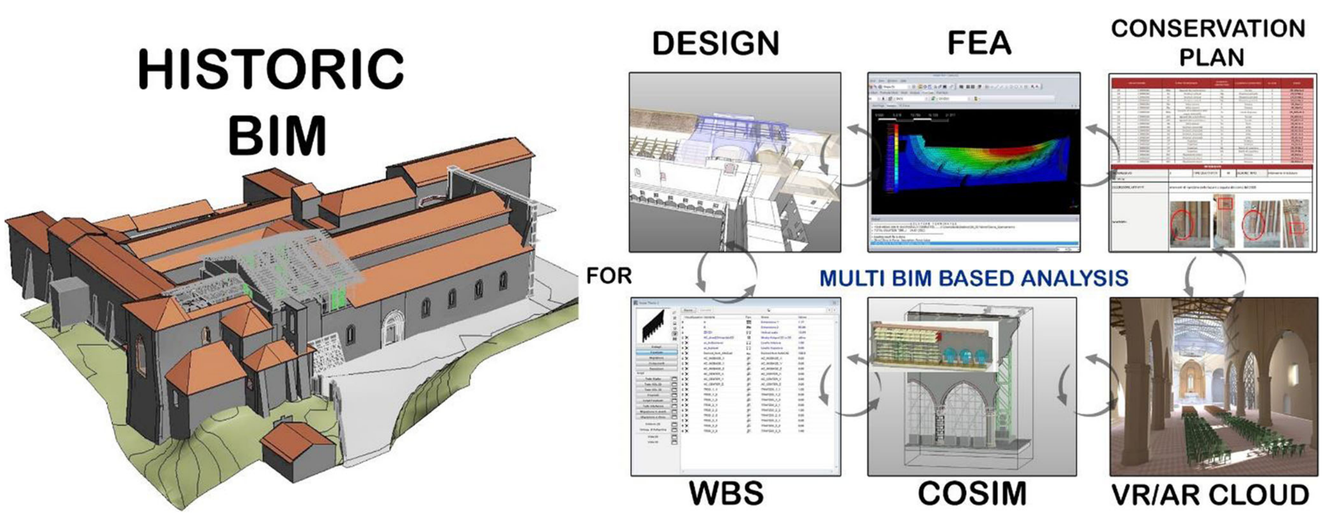


Fig. 7 HBIM cloud interoperability: the HBIM of the Basilica is fully interoperable with Design simulations, structural analysis (BIM to FEA), Conservation Plan and WBS activities (image courtesy of G. Utica), COnstruction Site Management (Co.Si.M) (image courtesy of M.A. Trani), and VR/Cloud liveBIM management within Virtual Reality by I-devices for on-site and touristic purposes

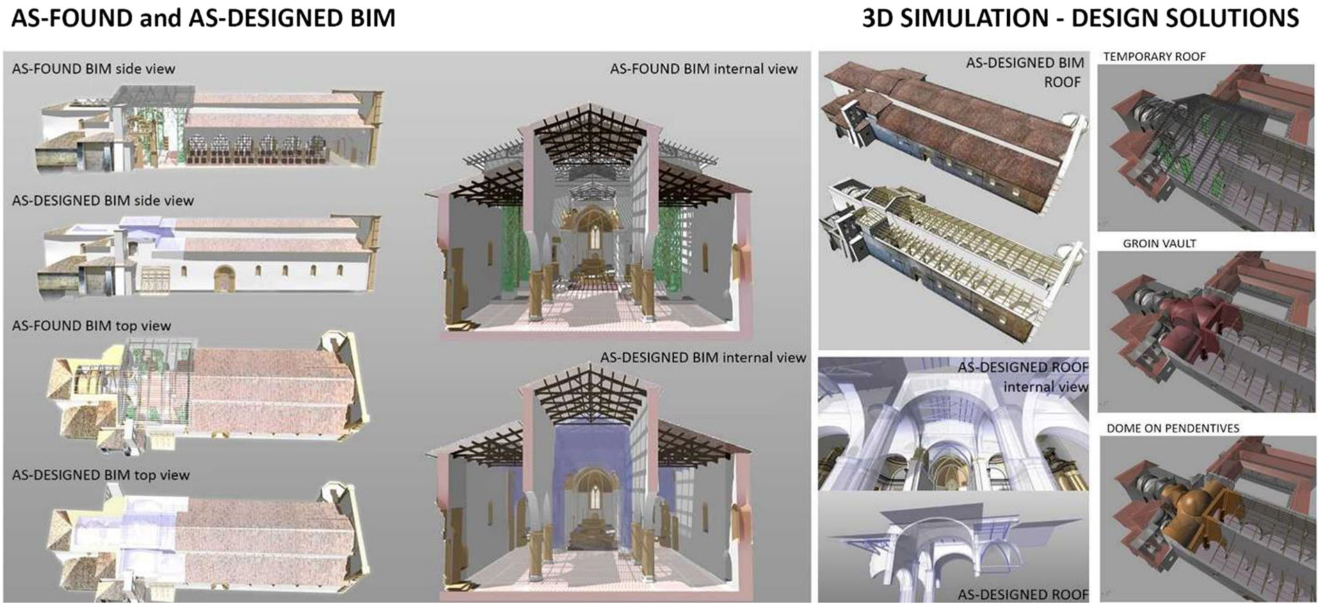


Fig. 8 The as-found and as-designed BIM (left-centre): the HBIM has been used to manage the different scenario simulation and solutions hypothesized in the design process (the case of the crashed dome): the groin and dome hypothesis (left); and the final adopted solution of the as-designed roof, integrating the new trusses, without the central dome (cen-tre-right)

- HBIM Preservation Plan management (from traditional 2D mapping of material and decay—"raumbuch" box based model analysis—to 3DHBIM-DB MGT-raumbuch): Level of Geometry characterized by LOD 500 (GOGs 1–10);
- HBIM to WBS (supporting Work Breakdown Structures, list of the activities and metric-estimative computation): Level of Geometry characterized by LOD 500 (GOGs 1–10);
- HBIM to FEA (HBIM 3Dcomplex Model LOD500: the challenge is to improve preservation of the single components and of the whole system interaction): pillars and fronts lesson learnt;
- On site MGT and HBIM as-built updating (LOD500 + LOD500–300);
- BIM toVR CLOUD to citizens' fruition via I-devices and phones (LOD 500).

From 2D to HBIM "3Draumbuch" (LOD500): NURBS-based mapping to support 3D graphic integration and management of the diagnostic phase (materials and decays)

The main peculiarity of BIM applications is the capacity to link various types of data and information to the 3D Objects, favouring the preservation plan and the retrieval of the information gained during the life cycle management (LC).

After an earthquake, an historical building can reveal several declines in conditions for the different structures and architectural surfaces. The detailed 3D representation of walls, masonry vaults and timbering elements is a fundamental step for identifying changes of planes, vertical settlements, rotation and out of plumbs (Cantini et al. 2008; Saisi et al. 2008). These geometrical indications are then associated to the crack pattern survey, a representation of the displacement of the structural cracks that can support the evaluation of the me-chanical behaviour of the building and its vulnerability to seismic actions (Anzani et al. 2008).

The interpretation of the crack pattern, when diffused on several architectural elements, is based on the comparison among the various fissures and their development: 3D layouts are commonly used for evaluating the relationship among the structural cracks and this representation can be implemented by BIM models.

Materials and decays maps provided the state of the art of the architectural surfaces of the Basilica along the walls and vaulted systems. According to the perspective of a conservation design, the material integrity of the building has been evaluated through detailed legends indicating the nature of each element and the alterations or decays processes afflicting them. These thematic maps are completed by a technical re-port providing a more complete description of the materials properties and the decays characteristics.

This series of operative document, map of materials, map of decays, crack pattern analysis and technical report, are strictly connected and future developments of HBIM could offer a new integration for these different contents.

Generally the thematic mapping of material, decay and design purposes are represented in a 2D representation obtained by the virtual rotation of all the faces of a virtual cube in a plan ("raumbuch" is the German praxis to document all the stratigraphic units along the wall surfaces in a room). The method is based on the integration of the thematic mappings drawings generally managed by 2D drawing into the 3D HBIM environment, with the generation of 3D objects corre-sponding to the various decay areas identified by the above analysis.

A system capable of linking and converting traditional CAD drawings into BIM objects, integrating them to the 3D parametric models is under development in order to manage the thematic mapping of materials and analysis of decay, starting from orthophotos of wall surfaces (Fig. 9). Figure 10 depicts the generative process, as previously explained, from the phase 2 (GOG9–10 NURBS based modelling phase), to the creation of accurate 3D parametric objects of each mapped element coming from the material analysis or from the related decay analysis. An external database (DB) of the materials and decays has been created to be managed within the HBIM.

3D BIM mapping generative requirements and specifications

Definition of protocols and generative is ongoing, thus experiments were performed on some selected test areas (i.e. the Holy Door façade, see also Fig. 10), and they can be articu-lated as follows:

1. Edge boundary extraction: to check the geometric boundaries of each decay area they must be properly created in traditional 2D CAD drawing application for the automatic recognition, reducing too dense polylines where possible and managing spline object.

2. Data management within modelling software and parametric environment:

- OPTION A. CAD to BIM: automatic map import from AutoCAD to Autodesk Revit ©, wireframe generation of each 3D mapping profile with the internal automation in Autodesk.
- OPTION B. Modelling software to BIM: orienting the geometric primitives within MC Nell Rhinoceros © and defining the exchange formats (3 dm to dwg) and requirements in order to assure the correct data management within BIM environment.

After an earthquake, an historical building can reveal several declines in conditions for the different structures and architectural surfaces. According to the perspective of a conservation design, the material integrity of the building is evaluated through detailed legends indicating the nature of each element and the alterations or decays processes afflicting them. These thematic maps are integrated by technical reports providing a more complete description of the materials properties and the decays characteristics.

Generating 3D BIM mapping of materials and decay by the 2D drawings allowed to embody within the HBIM deformations and cracks, relating them to the whole system, suffered damage and accurate quantification in one overall visualisation. Also, it allows to manage the information collected during the life cycle of buildings linked to the specific element.

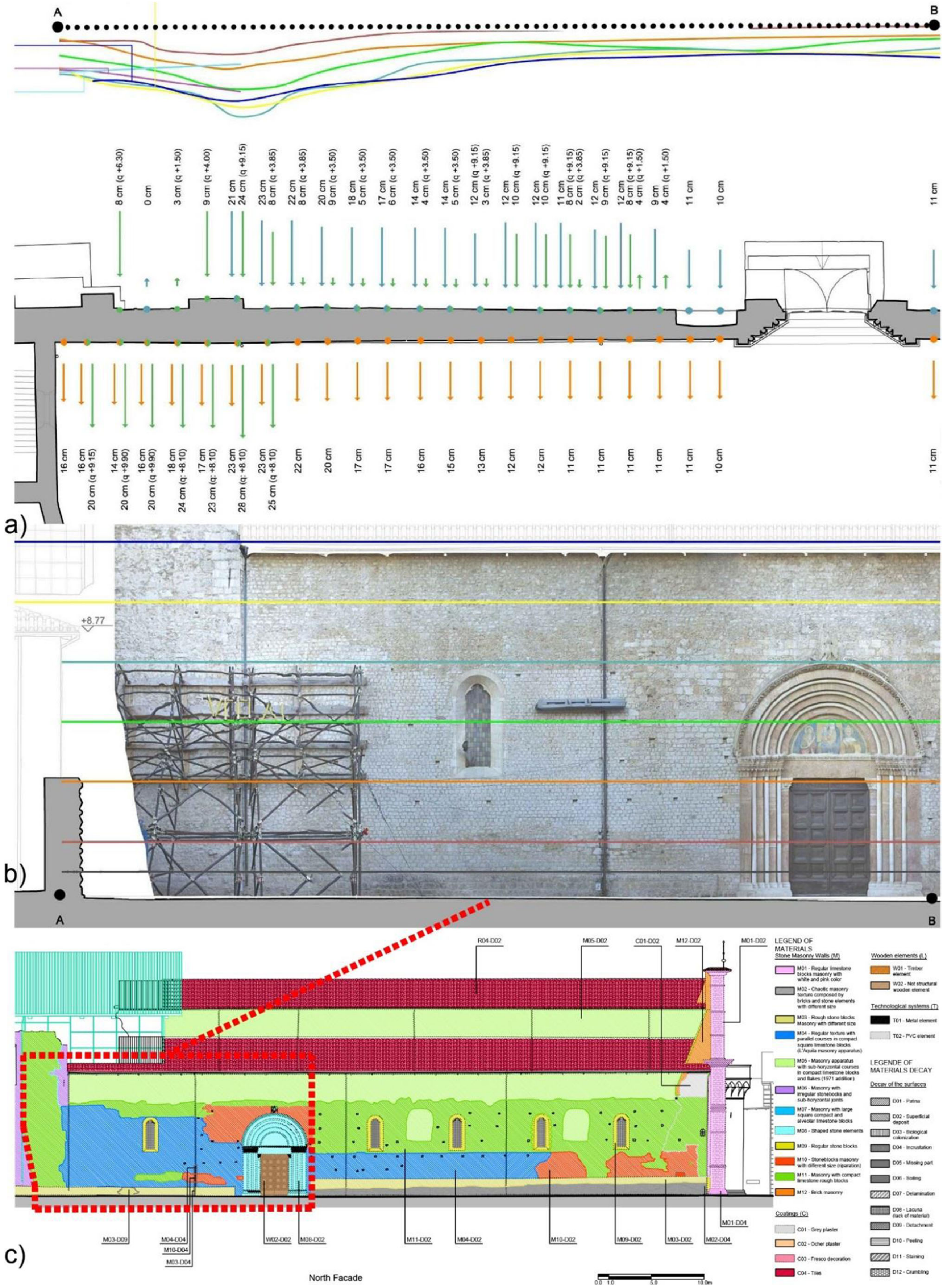
Thus, once each element is included in the digital system, the updatable process represent a virtual workspace of data sharing among different experts with possible feedbacks on decision making within a holistic approach gathering the contributions coming from the different disciplines.

The creation of specific objects made it possible to go beyond the simple correlation between drawing, 3D model and data. Each 3D element is associated with the following information: identification number, stratigraphic information on the wall such as materials, thickness, length, area, volume, resistance, thermal mass, decay analysis, different historical phasing and planned construction site phasing. The database has been created in order to improve the BIM interoperability toward the different actors (i.e. cost estimations). All these types of information allows a high level of sharing during the process of the restoration project of the Basilica for each parametric object and after the restoration updating the as-built phase.

HBIM to FEA: what is next?

After obtaining the HBIM model of each element as an instance object belonging to the different family categories (walls, roof, vaults), as described in the previous paragraphs, the overall sum of elements was tested to support a full interoperable HBIM devoted to the structural analysis and to the structural intervention. The HBIM was converted from the parametric BIM platform to FEA environment (Midas©), with the possibility of managing the Finite Element Analysis (BIM to FEA) using specific exchange formats and new modelling tools to support the structural choices. An overall model of the basilica managed by MIDAS© was obtained (Barazzetti et al. 2015b), entailing all the morphological complexity of each element without any simplification (Fig. 11). The generative modelling achieved the result to obtain a fully interoperable BIM model exported to the FEA environment (tool Midas©).

Fig. 9 The information to be managed by the HBIM on the North Wall of ▶ the Basilica di Collemaggio: (**a**) the wall geometry characterized by relevant out of plums (0–25 cm); (**b**) the 3D orthoimage (terrain pixel 2 mm) highlights the different arrangement of the stratigraphic units of the wall surface: on the right of the Holy Door is viewable an example of the "L'Aquila masonry apparatus" (M04—Regular texture with parallel courses in compact limestone block) as classified in the Material DataBase; (**c**) the 2D drawing of the thematic mapping (material and decay analysis) integrated on the 3Dorthoimages



A
B
8 cm (q +6.30)
0 cm
3 cm (q +1.50)
9 cm (q +4.00)
21 cm
24 cm (q +9.15)
23 cm
8 cm (q +3.85)
22 cm (q +3.85)
20 cm
9 cm (q +3.50)
18 cm
5 cm (q +3.50)
17 cm
6 cm (q +3.50)
14 cm
4 cm (q +3.50)
14 cm
5 cm (q +3.50)
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R04-D02
M05-D02
C01-D02
M12-D02
M01-D02
M03-D09
M04-D04
M10-D04
M03-D04
W02-D02
M08-D02
M11-D02
M04-D02
M10-D02
M09-D02
M03-D02
M02-D04
M01-D04
c)
North Facade
0.0 1.0 5.0 10.0m
LEGEND OF MATERIALS
Stone Masonry Walls (M)
M01 - Regular limestone blocks masonry with white and pink color
M02 - Chaotic masonry texture composed by bricks and stone elements with different size
M03 - Rough stone blocks Masonry with different size
M04 - Regular texture with parallel courses in compact square limestone blocks (L'Aquila masonry apparatus)
M05 - Masonry apparatus with sub-horyzontal courses in compact limestone blocks and flakes (1971 addition)
M06 - Masonry with irregular stoneblocks and sub-horyzontal joints
M07 - Masonry with large square compact and alveolar limestone blocks
M08 - Shaped stone elements
M09 - Regular stone blocks
M10 - Stoneblocks masonry with different size (riparation)
M11 - Masonry with compact limestone rough blocks
M12 - Brick masonry
Coatings (C)
C01 - Grey plaster
C02 - Ocher plaster
C03 - Fresco decoration
C04 - Tiles
Wooden elements (L)
W01 - Timber element
W02 - Not structural wooden element
Technological systems (T)
T01 - Metal element
T02 - PVC element
LEGENDE OF MATERIALS DECAY
Decay of the surfaces
D01 - Patina
D02 - Superficial deposit
D03 - Biological colonization
D04 - Incrustation
D05 - Missing part
D06 - Soiling
D07 - Delamination
D08 - Lacuna (lack of material)
D09 - Detachment
D10 - Peeling
D11 - Staining
D12 - Crumbling

The FEA (Finite Element Analysis) has been carried on in support of the structural analysis, addressing the intervention on the damaged pillars, the walls and vaulted system. Different ongoing experiences seem to demonstrate that parametrized complex object obtained by generative modelling can be transferred to FEA environments (Barazzetti et al. 2016); and the one reached is an important starting point, of course, in terms of potentials that can be opened. But in the structural analysis the current use of BIM is to derive the common level of simplification and schematization (i.e. linear schema pillar/beam in the case of an arched ancient bridge) bypassing the acquired model complexity (Martinelli et al. 2018).

A few open questions are arising in such context and in the particularly case of the Basilica of Collemaggio: did we manage the paradigm of HBIMs complexity linked to preservation challenges? In other words, can we boost the level of preservation challenging aspects tackling BIM tools and interoperability? How to reach it at a time-cost effectiveness favouring its adoption by the public and private subjects? Which lacks and gaps need to be overcome in the future, to exploit the acquired BIM modelling richness?

After this experience, we could say that one HBIM challenging issue is represented by their use in the structural analysis and decision making in the direction of boosting preservation aims. In theory, this result certainly represents an important step in the process linking HBIM complexity to the structural analysis domain. In the case of single elements data management (i.e. the pillars preservation), we could say that HBIM heavily contributed to support the preservation challenge, given that the demolition and reconstruction of all the pillars was one of the starting option and also one of the main arguing among specialists, restorers and structural engineers, among the different constrains, regulations on seismic risk reduction, the safety framework, and preservation aims.

On the other side the contribution of the HBIM model to the whole dynamic behaviour simulation to enhance the preservation requires to be further investigated.

HBIM challenge: protocols to lower costs and codifications

Scan to BIM process: filling gaps in time–cost effectiveness

Some comments can be carried out after 5 years of HBIM experience on the lesson learnt. Given the achieved HBIM generation managing morphologic complexity and unicity, many difficulties remain in using BIM for conservation projects, linked both to the complication in modelling irregular geometric elements, and to

Fig. 10 The different HBIM phases managing the material and decay ▶ analysis. Phase 2: from the 2D CAD traditional mapping drawings of materials and decays made on orthophotos of the fronts (upper left) to 3D BIM "raumbuch" management (upper right): the material and decay analysis are incorporated into the NURBS-based BIM model. Phase 4: HBIM Material and Decay Mapping DB management (centre): each material area is a parametric Object in the BIM DB inheriting the 3D shape of the Objects (i.e. walls, vaults), allowing to automatically deriving the information, like area and volume, and supporting cost analysis and metric computation of the different planned activities (WBS)

their adoption by administrators and construction enterprises who have to work in a new 3D environment from the traditional 2D.

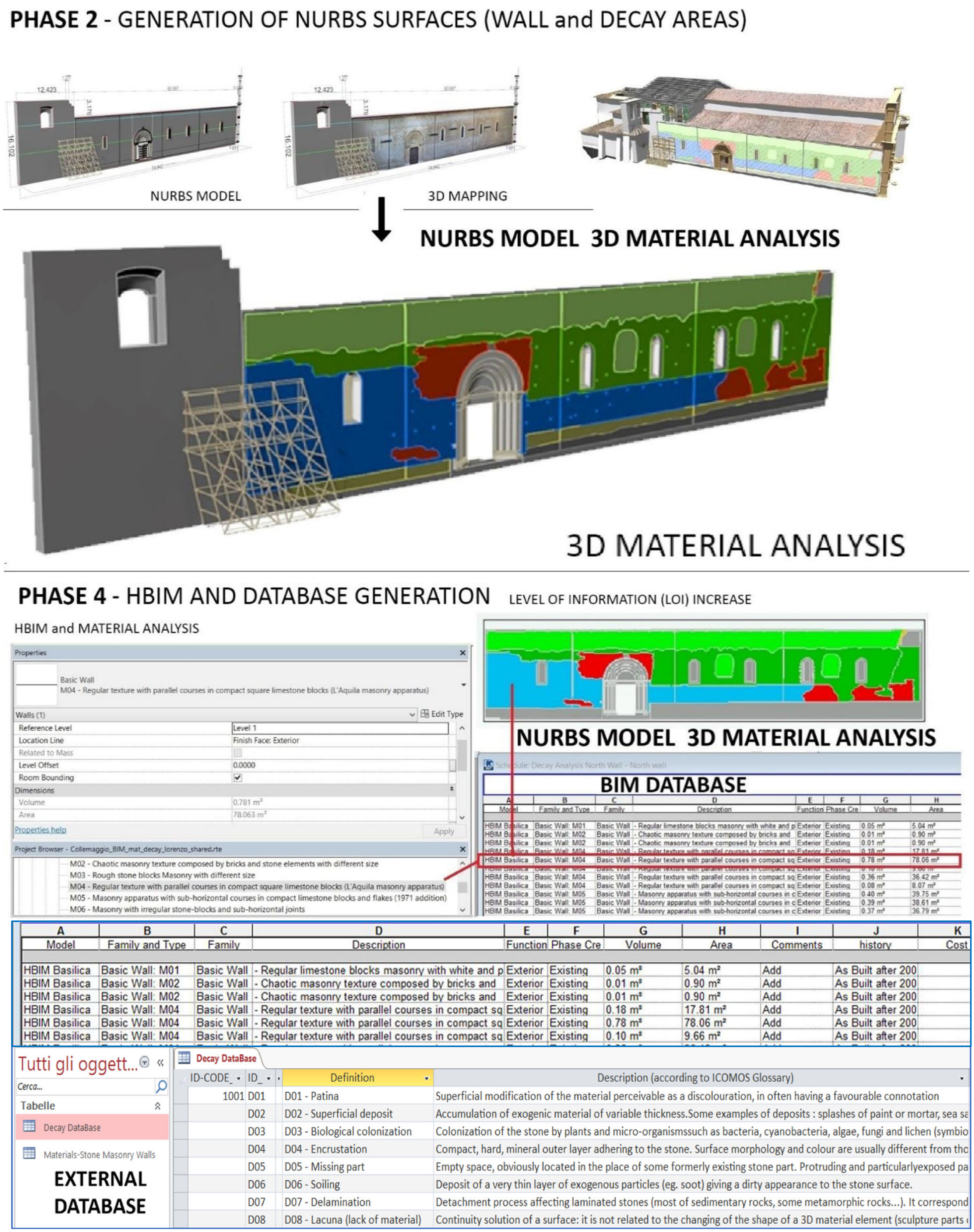
The challenge of HBIM-modelling capability and sustainability to support the overall behaviour and preservation decision making need to tackle active measures to increase time and costs effectiveness, to facilitate HBIM adoption in a massive way in the digitization process.

Few data have been extracted from the different phases, including surveying and HBIM modelling generation in term of personal effort and related activities (Table 1–Table 2). The tables show the great effort in terms of quantity but also the "sustainability" of the effort obtained through best practices in the modelling issues and improving knowledge transfer, taking in account that the skilled expertise will diminish the cost impact on future HBIM use. Particularly the adoption of GOG10 can accelerate the process maintaining the richness of the object without simplifying the morphology, as highlighted in the case of the arched nave walls and the vaulted system (Table 2).

Scan to BIM process: filling gaps in time-cost effectiveness.

These considerations lead the research toward the following directions to lower the HBIM take off costs:

- increasing technical skills lowering time-consuming modelling costs;
- boosting attitude toward interoperability among actors in the preservation plan and on-site preservation practices;
- introducing effective platforms to enable data exchange and adequacy of specialized BIMs in the different phases;
- introducing BIM modelling protocols and specifications to facilitate and accelerate the 3D HBI modelling process, preserving unicity and multiplicity of the architectural heritage;
- improving codification criteria linking HBIM to the design preservation process bridging the BIM into the monitoring, managing and maintenance phase, spanning its adoption to the Life Cycle Management;
- enhancing structural analysis taking into account the overall HBIM modelled to boost the knowledge and the preservation process.



PHASE 2 - GENERATION OF NURBS SURFACES (WALL and DECAY AREAS)
NURBS MODEL
3D MAPPING
NURBS MODEL 3D MATERIAL ANALYSIS
3D MATERIAL ANALYSIS
PHASE 4 - HBIM AND DATABASE GENERATION
LEVEL OF INFORMATION (LOI) INCREASE
HBIM and MATERIAL ANALYSIS
Properties
Basic Wall
M04 - Regular texture with parallel courses in compact square limestone blocks (L'Aquila masonry apparatus)
Walls (1)
Edit Type
Reference Level
Level 1
Location Line
Finish Face: Exterior
Related to Mass
Level Offset
0.0000
Room Bounding
Dimensions
Volume
0.781 m³
Area
78.063 m²
Properties help
Apply
M02 - Chaotic masonry texture composed by bricks and stone elements with different size
M03 - Rough stone blocks Masonry with different size
M04 - Regular texture with parallel courses in compact square limestone blocks (L'Aquila masonry apparatus)
M05 - Masonry apparatus with sub-horizontal courses in compact limestone blocks and flakes (1971 addition)
M06 - Masonry with irregular stone-blocks and sub-horizontal joints
NURBS MODEL 3D MATERIAL ANALYSIS
BIM DATABASE
Model
Family and Type
Family
Description
Function
Phase Cre
Volume
Area
Comments
history
Cost
HBIM Basilica | Basic Wall: M01 | Basic Wall | - Regular limestone blocks masonry with white and p | Exterior | Existing | 0.05 m³ | 5.04 m² | Add | As Built after 200
HBIM Basilica | Basic Wall: M02 | Basic Wall | - Chaotic masonry texture composed by bricks and | Exterior | Existing | 0.01 m³ | 0.90 m² | Add | As Built after 200
HBIM Basilica | Basic Wall: M02 | Basic Wall | - Chaotic masonry texture composed by bricks and | Exterior | Existing | 0.01 m³ | 0.90 m² | Add | As Built after 200
HBIM Basilica | Basic Wall: M04 | Basic Wall | - Regular texture with parallel courses in compact sq | Exterior | Existing | 0.18 m³ | 17.81 m² | Add | As Built after 200
HBIM Basilica | Basic Wall: M04 | Basic Wall | - Regular texture with parallel courses in compact sq | Exterior | Existing | 0.78 m³ | 78.06 m² | Add | As Built after 200
HBIM Basilica | Basic Wall: M04 | Basic Wall | - Regular texture with parallel courses in compact sq | Exterior | Existing | 0.10 m³ | 9.66 m² | Add | As Built after 200
Tutti gli oggett...
Cerca...
Tabelle
Decay DataBase
Materials-Stone Masonry Walls
EXTERNAL DATABASE
ID-CODE
ID_
Definition
Description (according to ICOMOS Glossary)
1001 D01 | D01 - Patina | Superficial modification of the material perceivable as a discolouration, in often having a favourable connotation
D02 | D02 - Superficial deposit | Accumulation of exogenic material of variable thickness.Some examples of deposits : splashes of paint or mortar, sea sa
D03 | D03 - Biological colonization | Colonization of the stone by plants and micro-organismssuch as bacteria, cyanobacteria, algae, fungi and lichen (symbio
D04 | D04 - Encrustation | Compact, hard, mineral outer layer adhering to the stone. Surface morphology and colour are usually different from tho
D05 | D05 - Missing part | Empty space, obviously located in the place of some formerly existing stone part. Protruding and particularlyexposed pa
D06 | D06 - Soiling | Deposit of a very thin layer of exogenous particles (eg. soot) giving a dirty appearance to the stone surface.
D07 | D07 - Delamination | Detachment process affecting laminated stones (most of sedimentary rocks, some metamorphic rocks...). It correspond
D08 | D08 - Lacuna (lack of material) | Continuity solution of a surface: it is not related to the changing of the shape of a 3D material element (sculpture parts

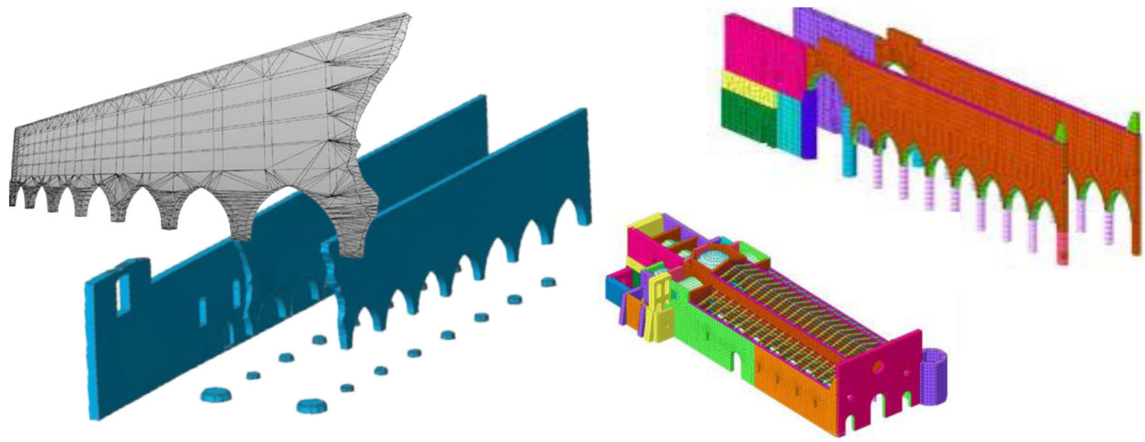


Fig. 11 From the NURBS based HBIM model of each element to the Finite Element Analysis model (Autodesk Revit© to Midas©). HBIM made by ~15,000 m^3 has been imported within MIDAS©. Images courtesy of ABC-Lab GIcarus Prof. R. Brumana, F. Banfi, and of Proff. P. Crespi and A. Franchi, and N. Giordano

Toward restoration codification criteria: UNI 11337-3-2017 (section 3-draft LOD/LOG/LOI to manage unicity)

The Collemaggio BIM experience anticipated the Italian Public Procurement Legislation (D.Lgs 50/2016, L. 21/06/2017 n.96, Nuovo Codice degli Appalti pubblici) that has been aligned with the EUPPD 24/2014: the EU Directive on Public Procurement asked all the 28 EU countries to adopt building informative modelling by February 2016 in order to support the whole LCM (Life Cycle Management), starting from the project and the intervention, through rewarding scores or mandatory regulations. Many analyses foresees, in fact, to save from around 5 to 15% of the overall investment by adopting mature BIM (levels 3 to 5), particularly 4D re-motely controlled BIM in support of the LCM, as in the case of maintenance and management process.

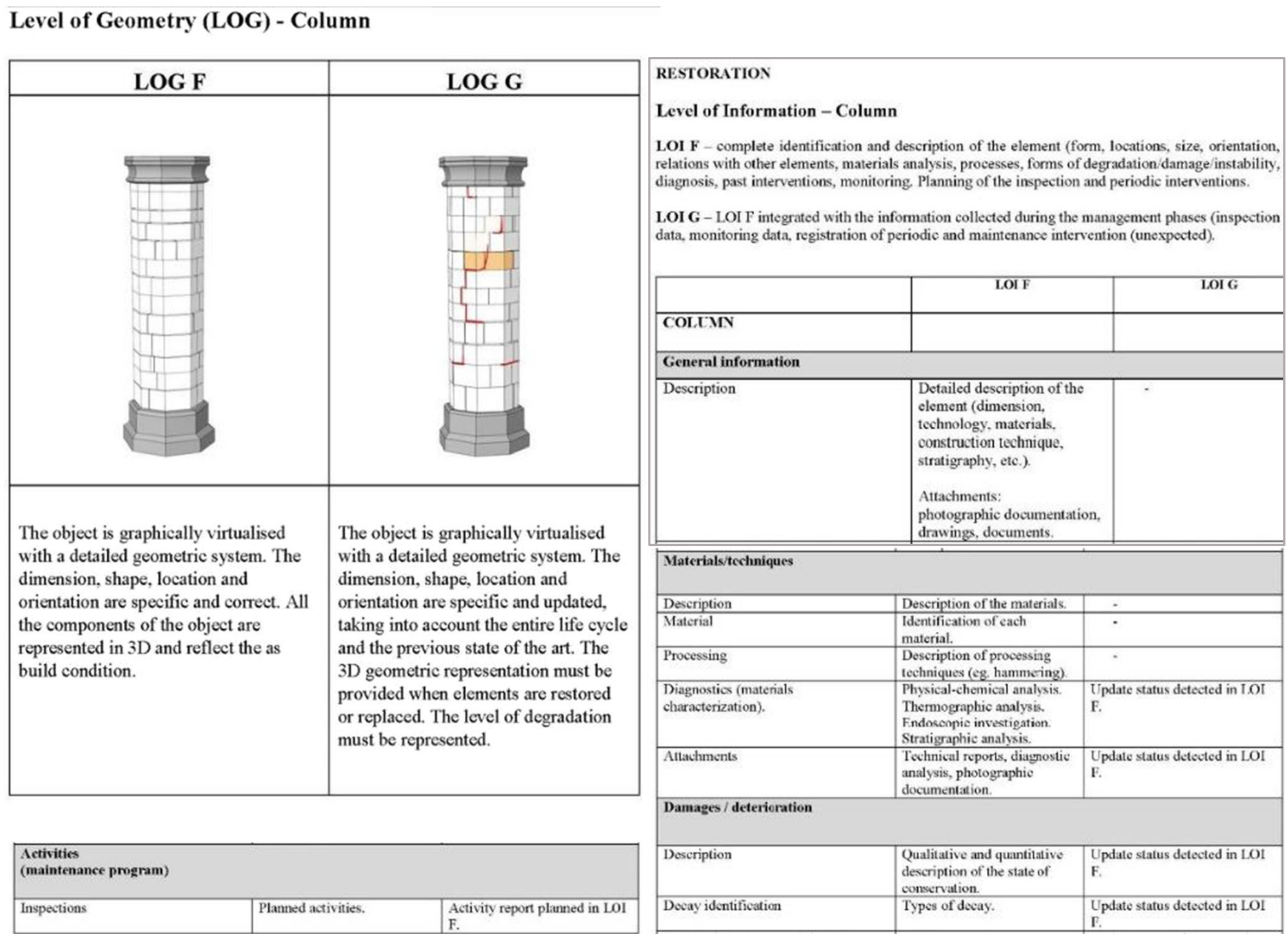
The tender for Basilica restoration was published in 2015 as a private tender. Nevertheless EniServizi separately funded the HBIM of the Basilica to tackle advanced digitization able to address decision-making processes among the different ac-tors, anticipating the spirit of the legislation in the most com-plex heritage domain.

Starting from different current BIM codifications in the international framework (i.e. AIA, AEC), and from the pro-gressively recognized HBIM specificity (Fai and Sydor 2013; Oreni et al. 2013), the lesson learnt from the Collemaggio HBIM contributed to address a drafted proposal of specifica-tion for the restoration domain, overcoming the UNI 11337-2009 Codification Criteria for Construction Products and Processes: the UNI11337-2017 (Sections 1-2-4-5) has been delivered on the LOD interpretation; the section 3 (LOG and LOI definition) is under discussion under the coordination of the Polimi multi-disciplinary subjects (UNI 11337-3-2017 draft). It has been proposed a specific Codification Criteria for the “Restoration” process domain (UNI 11337-3-2017 draft) defining a specific Level of Geometry (LOG) and Level of Information (LOI), on course of discussion at an international level (Fig. 12).

Independently from the formal numeric and alphanumeric sequences - that will be modified while enhancing BIM appli-cation in the experienced sectors (as in the case of the HBIM-Restoration) - the value of the new codification is to start facing the heterogeneous domain of the built environment linked to the BIM logic, as in the case of BIM LOG protocol definition for restoration.

The new proposed codification defines the common LOGs A–E, as adopted for the Information Requirement in the case of the new-construction—as “in-consequential” in the resto-ration project representation, with the exception of simplified specialist models (i.e. structural models): in facts, it introduces new ad-hoc LOGs “F–G” requiring explicitly a detailed geo-metric description of all the components of a building (LOG F), taking into account their unicity, the state of the art, the mandatory process of documenting materials and decay, to-gether with the updating of the interventions (LOG G). The codification process is trying to embody all the gained info within the HBIM itself. The Level of Geometry can be further enriched by the proposed GOGs 1–10 to describe explicitly the level of complexity and simplification related to the accu-racy check of the given morphology.

The draft of the section 3 also defines a related coherent Level of Information (LOI F-G) to be updated during the LCM and maintenance process. In fact the “as built” updating is required as a fundamental part of the chain from the state of the art analysis to the “longue durée” of the life cycle, follow-ing the different interventions on the object across the LCM, updating in the time the status detected including the material deterioration, damages. LOI F is integrated with the informa-tion collected during the management phases (inspection,



Level of Geometry (LOG) - Column

LOG F	LOG G
The object is graphically virtualised with a detailed geometric system. The dimension, shape, location and orientation are specific and correct. All the components of the object are represented in 3D and reflect the as build condition.	The object is graphically virtualised with a detailed geometric system. The dimension, shape, location and orientation are specific and updated, taking into account the entire life cycle and the previous state of the art. The 3D geometric representation must be provided when elements are restored or replaced. The level of degradation must be represented.

Activities (maintenance program)		
Inspections	Planned activities.	Activity report planned in LOI F.

RESTORATION

Level of Information – Column

LOI F – complete identification and description of the element (form, locations, size, orientation, relations with other elements, materials analysis, processes, forms of degradation/damage/instability, diagnosis, past interventions, monitoring. Planning of the inspection and periodic interventions.

LOI G – LOI F integrated with the information collected during the management phases (inspection data, monitoring data, registration of periodic and maintenance intervention (unexpected).

	LOI F	LOI G
COLUMN		
General information		
Description	Detailed description of the element (dimension, technology, materials, construction technique, stratigraphy, etc.). Attachments: photographic documentation, drawings, documents.	-
Materials/techniques		
Description	Description of the materials.	-
Material	Identification of each material.	-
Processing	Description of processing techniques (eg. hammering).	-
Diagnostics (materials characterization).	Physical-chemical analysis. Thermographic analysis. Endoscopic investigation. Stratigraphic analysis.	Update status detected in LOI F.
Attachments	Technical reports, diagnostic analysis, photographic documentation.	Update status detected in LOI F.
Damages / deterioration		
Description	Qualitative and quantitative description of the state of conservation.	Update status detected in LOI F.
Decay identification	Types of decay.	Update status detected in LOI F.

Fig. 12 UNI 11337-3-2017 (draft): the proposed section 3 on LOG-LOI ("F and G")

monitoring data, registration of periodic intervention and maintenance intervention, included the unexpected ones).

It is obvious that a great challenge, growing the specification requirements in the field of restoration, is represented by the sustainability of the HBIM process, starting from the modelling phase up to its operational use.

Final remarks

The Basilica of Collemaggio has been re-opened to the public on December 2017 (Fig. 13). Managing the paradigm of complexity represented by the specificity of each object instance allowed to enhance the knowledge from where to derive and

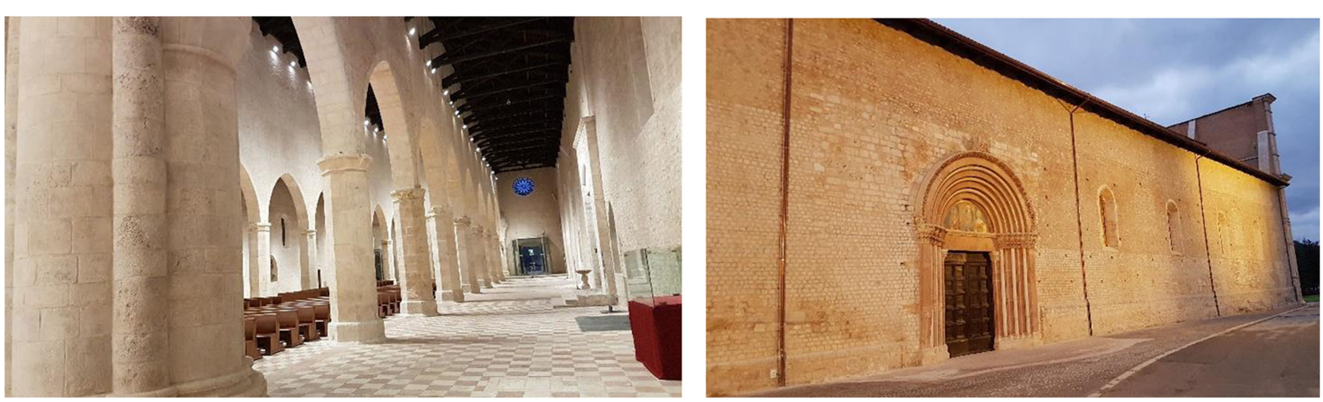


Fig. 13 Few results of the Basilica of Collemaggio re-opened to the public on December 2017. The cases of the pillars and north wall interventions

boost the conservation level. The possibility of having an accurate survey of the damaged structures and a detailed HBIM model was a great opportunity, not only in terms of knowledge enrichment, but also in terms of a project design that could be as close as possible to the real condition of the building, developing ad hoc solutions.

Getting a rich HBIM model starting from accurate surveys is an unavoidable starting point to enhance the conservation of the historical architectures: a step forward is needed to deploy the research toward a deeper comprehension of the whole behaviour taking in account the gained richness of each object of the Basilica together with the co-relation among them in order to improve the preservation issues in a safety context, boosting preservation of material authenticity and functional behaviour in a narrow challenging road.

The definition of different Levels of Geometry allows HBIM implementation taking in account the morphology of each component of the building starting from the accuracy of the surveying. Grade of Generation (GOGs 1–10) supporting simplified-to-complex model gains the result of obtaining model objects coherent with the geometry of each element surveyed (walls, pillars, arches, vaults).

Particularly NURBS-based modelling (GOG9–10) adopted for the HBIM of the Basilica achieved generating interoperable parametric objects that can be associated with different properties and information (LOI), as historical information and DBs, and at the same time interoperable with external programmes as well (i.e. BIM to FEA) or others for the different design and management purposes.

The HBIM of the Basilica di Collemaggio can now be conceived as a gateway to be constantly enriched with semantic vocabularies–as in the case of materials and decay or historical data–thinking of it as an innovative hub to access the digital tangible heritage artefacts, whose conservation represents the vehicle for transmitting historical information, transformation and richness of the construction together with intangible values represented by the past history among citizens. Codification criterion is progressively inheriting the specific requirement in the case of LOG and LOI definition in the specific domain of the restoration.

Also, the research contributed to start delivering modelling protocols, guideline, specification and codification criteria supporting the HBIM management across the time following its Life Cycle. Generative modelling protocols enhancement can contribute to diminishing the impact of BIM in term of time and cost effectiveness, accelerating the modelling phase and improving its use among multi-actors. Boosting attitude toward interoperability among actors in the preservation plan and on-site preservation practices is still needed, in order to gain effective operational cloud HBIM platform.

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