How to Measure Quality Models? Digitization into Informative Models Re-use

R. Brumana(✉)

Department of Architecture, Built Environment and Construction Engineering, DABClab-GIcarus, Politecnico di Milano, Via Ponzio 31, 20133 Milan, Italy
raffaella.brumana@polimi.it

Abstract. 3D models from passive muted subjects, often used in the books and in preservation design reports as powerful images dense of contents, have nowadays the opportunity to become 'live gears' leveraging knowledge, interpretation, and management into preservation objectives till to better-informed fruition. To this aim, we need to build up reliable and re-usable 3D Quality models. How to shift from a 3D model toward a 3D quality model?

This contribution intends to focus on the parameters defining a 3D Quality model catching the heritage complexity with its components in a holistic methodological and practical vision. A radar chart has been used to manage all the parameters. First of all, Geometry describes a quality model: parameters for data acquisition, on-site surveying, and model processing to obtain 2D-3D Geometry quality are defined. The concept of scale associated with measurable parameters defining the Grade of Accuracy is proposed and applied to the surveying and to the 3D models. 3D models can be considered tools to decode the complexity of cultural heritage made by the different transformations across the centuries, anthropic-natural hazards, climate change threats and events (such as earthquakes, fires, wars). Thus, Geometry is not enough to describe such complexity; it represents the first step. Materials and Construction technologies analysis is the second pillar qualifying a quality model. The connection with the indirect data source (i.e., historical reports and archives documents), is the third pillar to be reconnected to the Geometry and Material analysis in the quality definition. HBIM represents a multidisciplinary environment to convey the information related to geometry and models. Furtherly, several parameters are identified to describe the quality of informative models, as in the case of Object Libraries and Building archeology progressively feeding such models. BIM Level of Developments (phases) and Level of Geometry (contents, not scale!) have been adapted to the HBIM, introducing digitization, surveying, and HBIM modeling into the preservation process. Finally, a quality model is defined by the capability to be re-used circulating Information and Models among the end-users as in the case of informed VR/AR through CDE and XR platforms.

Keywords: 3D Quality models · Complexity · HBIM · Heritage Building Information Modelling · construction systems · monitoring · Scan-to-HBIM · modeling · generative modeling · Scale · GOA · LOD · LOG · building archaeology · 3D volume stratigraphy · CDE · VR/AR/MR · XR

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1 Introduction

The digitization processes need a systemic approach, generating holistic multi-faceted models: 'live' digital twins continuously growing within a complex built environment, under the hazards, natural anthropic pressures as climate change, earthquakes and at the same time inheriting the complexity of the past.

It can be helpful to remember the deep meaning of the term "complex" from Latin "*complector"*, hold tightly, and, metaphorically, gird, embrace, and comprehend.

Edgar Morin "From the Concept of System to the Paradigm of Complexity" [1]: "*In order to make sense of the concept of system, we must postulate a new, nonholistic principle of knowledge. However, this will be possible only if we conceive of systems in general and generic or generative terms- that is, in terms of a paradigm. A paradigm being defined here as the set of fundamental relations of association and/or opposition among a restricted number of master notions-relations that command or control all thoughts, discourses, and theories)".*

"… Finally, there is the impossibility of understanding a complex mental structure from the wall of a reductive or simplifying mental structure (while the inverse is possible)". Morin asserts that to know is to separate, to analyze and reconnect to synthesize or make complex, to '*complexize*'.

What we can derive, among others, from this assertion is that complexity need to be intended as a circular process, where we can separate and filter some aspects to understand some aspects: but they require to be reconnected at a further step; as well as we can't simplify at the beginning but at the end.

2 Complexity and Quality: #Parameters into a Multiple Variable Radar Chart

3D quality models can help in driving complexity: moving from their 'limbo', between media, society of image and big data circulation thanks to the technological potential offered by digitization; moving from a substantial under-use toward their re-use supporting preservation analysis and activities during the extended life cycle maintenance, and data transfer toward a better communication rising awareness through informed contents.

To become subjects of knowledge, they need a qualitative leap addressed to content creation-content use-content transferring-content re-use.

Objectives of 3D quality models can be summarized as follows:

- to better understand the current geometric asset (addressing surveying methods and 3D models to embodying and registering the richness of geometries, anomalies, out of plumbs, profiles comparison at the different levels, different alignments of the portions of the construction periods);
- to support the assessment and the data interpretation, understanding and connecting all the different data (i.e., materials, decays, different transformation phases, global and punctual behavior, including the structural behavior);
- to drive the preservation plans starting from understanding and interpreting state of the art to drive the design and decision making;

- to prevent future damages fostering the planned preservation (Long Life Cycle Management and Maintenance);
- to deploy knowledge transfer of enriched models among different operators;
- to promote the re-use and circulation of knowledge sharing for dissemination purposes (MR/VR/AR).

Different parameters (#parameters) describing the quality of surveying till to the data management and re-use of the informative system (HBIM) are hereafter identified. This paper is part of the result of VIGIE expert member's research on the "Study on quality in 3D digitization of tangible cultural heritage" [2]: a radar chart has been set up by the coordinator to manage all the parameters identified by the different contributions to the multiple tasks [3].

The proposed radar quality diagram is here applied in the following paragraphs to one of the selected success story case studies (the Basilica di Santa Maria di Collemaggio), considering the multi-variables crossing surveying, processing, and data transfer, when facing the heritage complexity. Such parameters are hereafter described to measure the contents enriching the quality model: geometry, model scales, grade of accuracy, materials, construction techniques, informative systems, content transfer, building archeology, level of development and level of geometry, Long Life Cycle management through Common Data Environment.

2.1 A Success Story into the Radar Chart: The Basilica di Santa Maria di Collemaggio (L'Aquila, Earthquake 2009) Reopened to the Public in 2018, Awarded by Europa Nostra 2020

The project 'Re-start from Collemaggio' is here considered to derive the lessons learned crossing the digitization process finalized to the preservation after the earthquake, helping to define the concept of quality and complexity when dealing with a challenging context and a stratified architectural document. According to the stakeholder requirement (the Superintendence Office), the generation of an advanced HBIM based on reliable surveys to address decision-making by the different actors involved in the preservation process has been undertaken [4]. This case study has been used to describe the parameters proposed to measure the quality and results obtained. The Italian multinational energy company (EniServizi), after the earthquake occurred at L'Aquila in April 2009 (Fig. 1), launched the project "Re-start from Collemaggio" funding around 16 million Euro to preserve the damaged Basilica. HBIM model of the Basilica of Santa Maria di Collemaggio supported the preservation design project and the restoration after the earthquake (L'Aquila, 2009).

The Basilica of Santa Maria di Collemaggio received the European Heritage Award/Europa Nostra Award (2020, May 07, | Conservation | Italy | L'Aquila), [4]. The Basilica attracts about 30,000 people for the Forgiveness Feast Day (Festa della Perdonanza) on 28-29th August, established by Pope Celestino V (before the Jubilee - 'Giubileum' - set up by Pope Bonifacio VIII recurring in the world every 25 years). The Feast is celebrated with the procession ceremony to the Holy Door of the Basilica: it represents an extraordinary unicum of tangible and intangible values. The design and the preservation have been intended to transfer them to the future. The Basilica successfully reopened to the public in December 2017.

Fig. 1. The area struck by the earthquake at L'Aquila and the damaged Basilica di Collemaggio

3 How to Define the User Needs? #*Scale* as a Parameter

User needs requirements are fragmented depending on many factors and circumstances, including funding availability. The decision to choose a high-medium-low level of precision and accuracy depends on many factors. It requires to be coherent with the state of art. It needs parameters to address the surveying since the starting phases. But sometimes, even if we are in a complex contest needing a high level of precision, due to the state of the art, the decisions are not or can't be coherent and consistent.

Thus the decision among high-medium-low level of details and contents requires to be transferred to the users with transparency to avoid mismatches during the use and re-use. Models, once generated, need to be circulated and re-used, sharing all the knowledge and Information. Information are progressively growing within the multidisciplinary preservation process, supporting sustainable interventions.

Models are expected to support users, experts and non-experts to extract content. Models need to become a live instrument to accompany all efforts to transmit cultural heritage to future generations, throughout the preservation of all its materials together with construction technologies, considered in their physicality, a vehicle of immaterial, tangible and intangible contents.

Given that object models are generated by different professionals for different uses (with different required precisions and details), this paper intends to identify the parameters describing a quality model rising situational awareness among the experts and operators in the re-use of such models.

Thus, the adoption of simplified models needs to be declared in order to avoid faulty inferences when comparing or re-using libraries of objects modeled with different precision and accuracy.

3.1 How to Measure Quality Model? Surveying to Digitization: Scale as a Parameter to Check Quality Control and to Re-use Models

#Scale parameter. A feasible model is based on a reliable data acquisition starting from the on-site surveys! Model scale can be a parameter to measure the quality: to this aim the HBIM Grade of Accuracy (GOA) is here inherited and associated to the different scales; the concept of scale can be considered as a switch to guarantee the user needs freedom of choosing the 3D quality model most appropriate to their different objectives; at the same time, to ensure a coherent use of such models being the users aware of the low-medium-high level of accuracy (scale) of the data collected and processed.

A 3D quality content model starts from the proper identification of the instruments and methods to acquire and process the data. The scale concept can be considered a parameter for selecting the proper instruments (precision) and reliable processing to obtain reliable results (accuracy). The concept of scale is commonly adopted by professionals (i.e., architects, engineers), even if qualitatively. The higher is the scale, the higher is the level of detail. But the scale concept has a robust meaning, mostly unknown: it allows to handle measurable parameters under a qualitative and quantitative point of view. Scale requirements have been adopted for many decades in the tenders' specifications at a worldwide level. As it is in the case of the generation of technical maps at the cartographic scale: the scale 1:25.000 has been adopted for territorial maps (i.e., IGM maps by the Istituto Geografico Militare/Geographic Military Institute), the scale 1:10.000 and 1:5000 has been adopted for the technical regional-scale maps, 1:2000–1:1000–1:500 for the municipality technical maps. The specifications are standardized in the aero-photogrammetric process in the cartographic domain and inherited by the architectural surveying specifications (i.e., 1:100–1:50–1:20–1:10–1:1).

3.2 3D Quality Content Models: #scale as a Parameter to Select the Proper Instruments and to Process Reliable Data (Precision and Accuracy): Specifications, Scales of Representation, Minimum Detail, and Tolerance Parameters

#Scales parameters: minimum detail and tolerance. Several specifications have been fixed to guarantee the required accuracy in the map generation since the starting phase of the data acquisition through the data processing. The two parameters conventionally adopted to measure the scale are (i) the minimum level of detail (the so-called Graphic Error, G.E. fixed = 0,2mm for all the scales) and (ii) the related Tolerance (T) = 2 ÷ 3 G.E (Table 1). The choice of the 'scale' depends on the survey's objective and on the use of the final product: such parameters allow to identify the proper scale, the proper instruments, and methods of processing, to validate the output and to re-use the output (Fig. 2).

For example, at 1:50 scale, the G.E. value is 1 cm, and 2,5 cm the tolerance (T). In the case of photogrammetric restitution (as rectified images or orthophoto), the minimum detail of the data acquisition is fixed at half the G.E. value at the given scale, with a restrictive requirement in order to consider the processing resampling.

 # 3D Model Parameter (Grade of Accuracy). The concept of Grade of Accuracy (GOA) has been related to the scales (GOA10, GOA20, GOA50, GOA100) and proposed to describe also the 3D object models quality [4], thus defining the minimum detail and tolerance values in the modeling generation (Fig. 2).

The Grade of Accuracy of the different scales is associated with G.E and T parameters [5]. The identification of the surveying instruments and restitution scale needs to be coherent with the correspondent parameters to make them reliable for the different uses and user needs (Table 2): 3D Geometry Scale and Image Scale are defined through the given parameters (Fig. 3). The precision of the surveying, as in the case of cloud scans acquired with TLS (i.e., laser scanner FARO Focus 3D), allowed the extraction of vertical and horizontal profiles with high accuracy (2 ÷ 5 mm), thus coherent to the scales GOA20- GOA50. Even if we assume a 1:50 model scale, the precision related to the surveying method, as profiles for geometric analysis or out of plumbs analysis, is

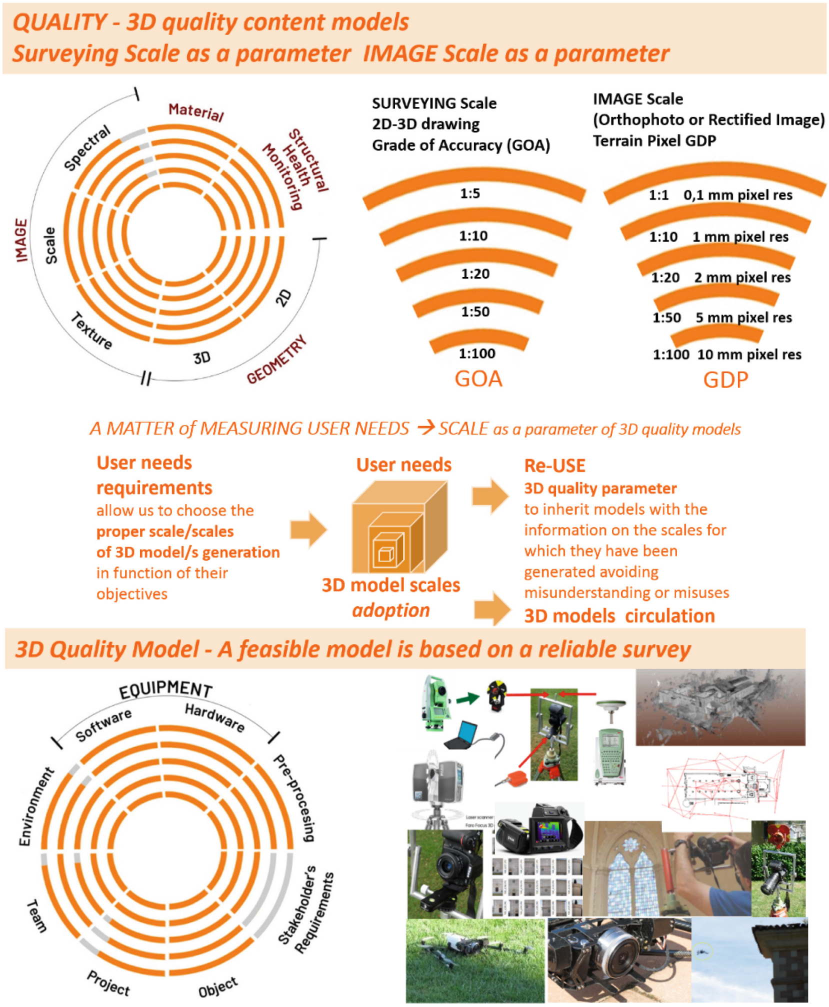

Fig. 2. Scale as a parameter of surveying, 2D drawings, 3D models, and HBIM: it is inherited from the technical cartographic maps specifications, here applied to the 3D model objects

relative to 1:20/1:10, and it will joke in favor of the object model that will be generated. Viceversa, Mobile Mapping Systems (as ZEB GEOSLAM), very useful for massive data acquisition, have a precision coherent with a scale range 1:100–1:200.

Using the conventional definition of Graphic Error fixes the smallest detail that can be represented at a given scale (G.E. = 0,2 mm), and of the related Tolerance (T = 2 ÷ 3 G.E. value), we can apply such values to all the different model scales obtaining indicators of precision and of interchange in the usability and data sharing among actors and experts. As an example, the mosaic floor of the Basilica of San Marcus has been realized at a 1:1 scale to support the maintenance intervention on the single 'tessera' maintaining the 3D waved shape [6].

Table 1. Scale as a parameter to measure surveying, 2D drawings, 3D models, and HBIM: it is inherited from the technical cartographic maps specifications and here applied to the 3D model objects associating the Grade of Accuracy to the scale concept.

Survey Drawing 3D model and HBIM SCALES	Minimum Detail Graphic Error (G. E.) = 0,2 mm	Minimum detail in case of image/ raster data (G.E.) = 0,2 mm/2	Tolerance Value T = 2 ÷ 3 G.E	HBIM models generated at different scales GOA Grade of Accuracy
1:1	0,2 mm	0,1 mm	0,4 ÷ 0,6 mm	GOA 1
1:10	2 mm	1 mm	4 ÷ 6 mm	GOA 10
1:20	4 mm	2 mm	8 ÷ 12 mm	GOA 20
1:50	10 mm	5 mm	20 ÷ 30 mm	GOA 50
1:100	20 mm	10 mm	40 ÷ 60 mm	GOA 100
1:1000	200 mm	100 mm	400 ÷ 600 mm	GOA 1000

Fig. 3. Geometry and image scale are parameters of 3D quality models: their components can be acquired and processed at different scales. Courtesy of ABClab-GIcarus (F. Banfi, R. Brumana)

The proposal is to apply the surveying specification concept, traditionally linked to the representation scales, also to the 3D quality models, and to the HBIM model objects. GOAs are proposed introducing Levels of Accuracy linked to the scale measurability, inherited from the BIM logic and adapted to the heritage preservation purposes, referring to the richness of model details. In the modeling generations, GOA20 model accuracy has been adopted for vaults components in the Basilica di Collemaggio, GOA10 model for the octagonal columns, etc.

Table 2. The results obtained by the surveying: instruments precision, methods, and accuracy as parameters for reliable results of the 2D-3D output (restitutions of plans, sections and fronts)

Surveying methods and output	Required scales and Survey methods *Few quality figures…*	Accuracy (mean square error, s.q.m.)
Geodetic Network	27 stations Total Station Leica T70	$\sigma = \pm 1$ mm
Geodetic Control Points	260 points Total Station Leica T70 (GCP for Scan REGISTRY and GCP for SFM images)	$\sigma = \pm 1.5$ mm
Laser Scanner Faro Focus 3D	182 point clouds (with geodetic network and GCP data registry)	$\sigma = \pm 3$ mm
Direct hand survey of the column stones ashlars	n. 14 Columns geometry 1:10; tot. 574 stone ashlars (9 ÷ 13 column courses at 1:2 scale) *TOT ~ 53 m^3*	
Photogrammetric image blocks Ortophoto / 3D models (i.e., external and internal walls surface vaults intrados)	Ground Dimension Pixel (GDP) - Terrain Pixel Resolution: 5mm (external fronts 1:50); 2mm (internal fronts, north damaged wall and main façade 1:20); 1mm (vaults intrados 1:10); 0,5mm (the main facade 1:5); *TOT ~ 7.000 m^2*	5mm (1:50) 2mm (1:20) 1mm (1:10)
Plans (horizontal sections)	1:50 Ground level (3000 m^2), underground, crypt, first floor 1:20 walls profiles for 3D model analysis 1:5 columns (out of plumbs) TOT ~ 4200 m^2	$\sigma = \pm 3$ mm
Vertical Sections (transversal and longitudinal sections)	1:20 - 12 sections with double view direction (and fronts integration)	$\sigma = \pm 3$ mm
UAV Falcon8 Covering and facades	RGB (GDP 10 mm-5mm) 1:100–1:50 IRT flights (GDP 1 cm)	TOT ~ 3000 m^2

4 Beyond Geometry Through Geometry: # Parameters to Manage Informative Enriched 3D Quality Models Contents Transferring

 # 3D Geometries. Geometries can be intended as the result of the wealth of details ensured conjugating massive data acquisition with high accuracy; advanced processing methodologies supporting the representation of the complex geometries are capable of shaping the uniqueness of the architectural complex and its components.

As explained in the previous paragraph, it requires an advancement on the specifications to identify the proper model accuracy, scale, and richness of details to decode, analyze and represent heritage complexity as a whole and, at the same time, in its components (i.e., structural elements, vaulted systems, columns, walls, till to the decorations, frescoes and stuccos). 3D models, once generated, start circulating to be re-used and shared by common data environments and platforms: thus, they need to be validated not just on the surveying side but also on the modeling and processing side. AVS available tools can be easily used.

But precision is not enough!

Models can be enriched by different parameters going beyond the geometry but intrinsically connected to the geometry. Hereafter, a list of parameters contributes to 3D quality models till to the informative system enrichment.

 # Generative Modeling, HBIM Enabling Models. The generative model process is a crucial parameter to get the Object models at the required scale starting from reliable surveys. Proper procedures of NURBS generative modeling contribute to guarantying the interoperability among pure modelers and parametric modelers, avoiding simplifications derived from not fully enabling models, enhancing capacity building, and upskilling among users and modelers (Fig. 4), [7].

The quality of a HBIM model depends on many parameters: the capacity of the model to embed geometry, images, radiometric information. It requires proper processing to get NURBS based Material (and Decay) Mapping as illustrated in the following paragraph, in order to support data management, and related metric computation (i.e., Area, Volume) together with all the information.

4.1 Not Just a Matter of Measuring: Geometries Embodying Materials and Construction Techniques Through HBIM

Not just a matter of measuring: a quality model cannot be defined just by its geometric accuracy. We have to add parameters that come from the material analysis supported by high-resolution photogrammetric data processing: as in the case of rectified images and orthophoto to be associated to the 3D models: geometries embodying materials and construction techniques contribute to defining enriched 3D model. And, vice versa, geometries and interpretation coming from the materials and construction techniques can improve the 3D Quality Model.

#Informative Quality Models (as HBIM, GIS and DBS). Model objects can be progressively enriched by the Information, within the informative models; they support different BIM uses (as the preservation design project, the conservation plans, the materials, decay analysis, construction techniques, structural behavior, Finite Element Analysis, energy performances) and decision-making processacross the life cycle management (Fig. 5). Parameters define which Information are required to be detected and described at the HBIM Information level are fixed by the conservation experts.

#Mesh Based Surfaces. We have many meshes circulating and coming from automatic processes by the users, architects, and engineers, thanks to common tools (as in the case of photogrammetric textured models) that could be very useful if used to enhance the content interpretation. In general, they are destined to remain at a passive level, used as background in the BIM tools. Enabling 3D meshes to embed all the properties Information and connections to external DB, as for costs computations, means to turn them into Object Models within HBIM.

#Shifting from Surfaces to HBIM Object Models. We need a shift from the surfaces to the object models. Surfaces are the first sentinel that can be easily surveyed, but we have to take into account that the surfaces are just a face of solid objects components of the architectural heritage or archeological site. We need to go behind the surfaces, to understand the Object that has been built and transformed across the centuries with all the decay and issues in order to manage quality models and not just the skin surface! 3D Object shifting means recognizing the 'habeas corpus' of each component as an identity card. A wealth of knowledge to valorize the uniqueness of all the architectural components: each Object description is a 'unicum' made by geometries integrated by materials and construction techniques.

#Mapping Materials, Construction Techniques, Decay. Knowledge of materials and construction techniques - including the techniques of craftsmen transferred from generation to generation across the centuries – are parameters enriching models quality. Material analysis, as well as decay analysis, can be mapped generating HBIM Objects to be managed with external Databases that can be added to the Information by the preservation experts and professionals [8]. 3D HBIM quality models can conjugate geometry with surface texturing (Fig. 5). Moreover, as demonstrated by many kinds of research, the geometry is influenced by the construction techniques as in the vaulted systems where the shape is influenced by the arrangements [9].

 # NDT. Non Destructive Techniques (i.e., IRT Infrared thermal cameras, NIR Near-Infrared cameras, Hyperspectral data, geo-radar, sonic analysis). NDT can be useful to better understand - behind the surface plaster - the arrangement of different stratigraphic units as well as chimney channels [10]. Here applied to the vaults with a passive method (a parameter to be considered), thus with fewer results than the rooms' active heating, unfortunately here not possible for the contest.

#Correlating Material Analysis to the 3D Arrangement. 3D content models capable of decoding the complexity of behavior that comes from the stratified transformation phases impacted by hazards in a fragile context.

The out plumbs after the earthquake, the anomalies, the irregularities, the reading of the different stratigraphic units, the relations among the different components (as columns-arches-naves) allowed us to better understand the disconnections and the damages preventing disjoining with proper connections in the preservation plan.

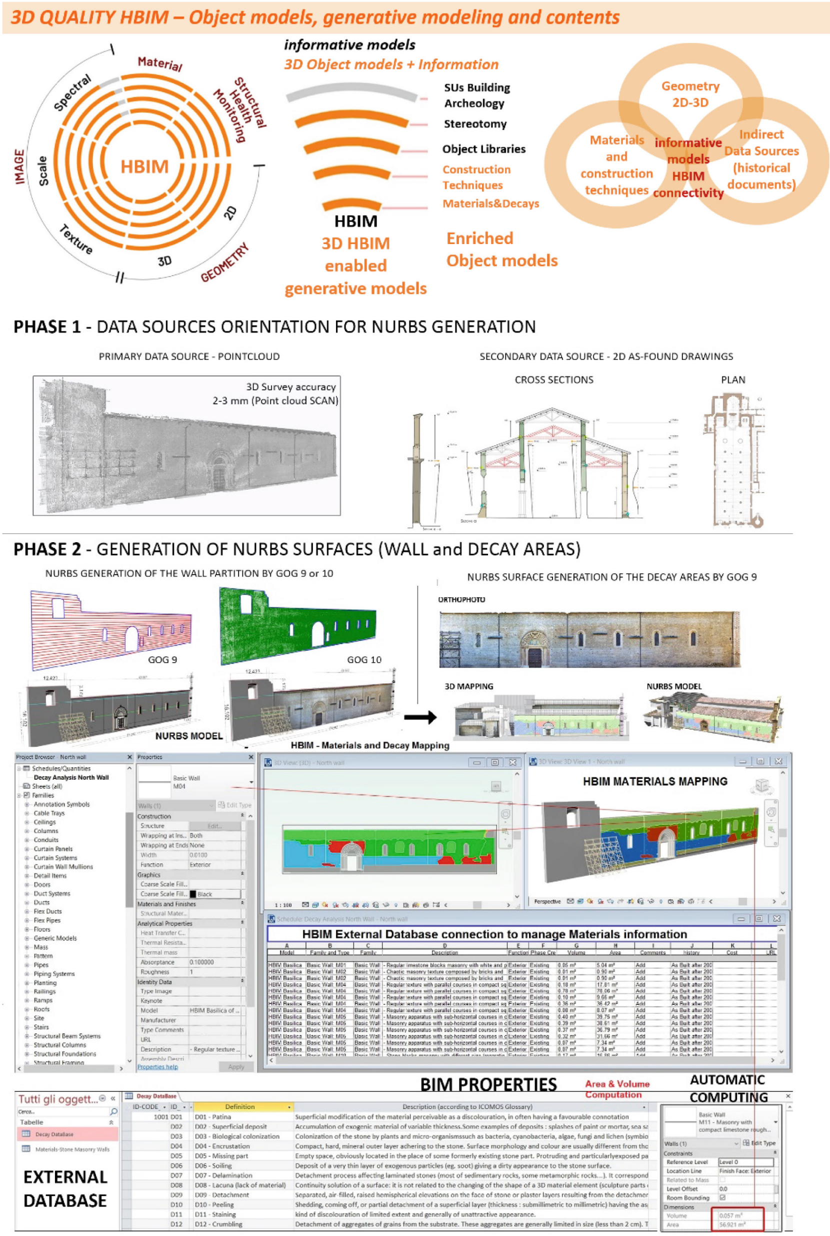

Fig. 4. The quality of a model depends on the generative model process to get the required scale starting from reliable surveying. Material and Decay Mapping as a parameter of quality for HBIM data management: NURBS model supports the HBIM Material mapping process. Courtesy of ABClab-GIcarus (F. Banfi, C. Stanga, R. Brumana)

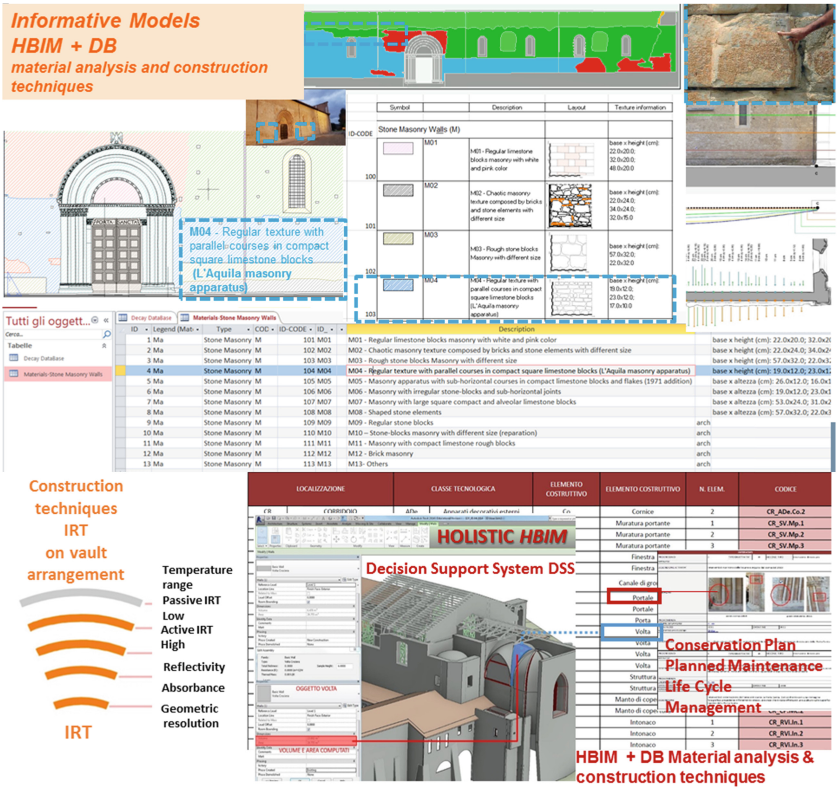

Fig. 5. Materials, construction techniques, and IRT analysis, together with the decay analysis, embedded within the HBIM, supporting the conservation plan Work Breakdown Structure linked to the Object models. 3D volume stratigraphy was not integrated into the HBIM. Courtesy of ABClab-GIcarus (F. Bafi, D. Oreni, L. Cantini, R. Brumana)

#Stereotomy. High-quality models digitization is returning to us the history of constructive wisdom and the art of cutting stones in the space (stereotomy): complex shapes not belonging to the simplified typological classifications cited in the historical manuals, give back us masonry techniques with a multiplicity of results. It is the case of 'Trompe' shaping (Guarino Guarini) or framed vaults across Europe with the art to build in the space complex models saving wood centerings fasting the construction process with a unique variety of solutions [11].

HBIM models of all the columns embody the out of plumbs together with the 3D shaped ashlars elements with the hands-on survey of all the damaged ashlars (Fig.6): it was hypothesized an average of 35% of damaged ashlars (yellow) to be necessarily substituted during the intervention, in the consciousness that this percentage would undoubtedly increase during the works. But it contributed to hypothesize the 'scuci e cuci' to reduce the replacement to the damaged elements.

#HBIM Object Libraries. Each single informative object model – considered as a node - can contribute to the generation of libraries of the objects across space and centuries; these nodes can be compared highlighting permanence and mutations of the construction techniques, highlighting the unsuspected richness of the vault systems generating HBIM based inventory [12]. Criteria and tools to catalogue brick-masonry vaults through informative geographic models contribute to describing the specificity and richness of the architectural components [13], fostering the history of historical construction techniques [14].

To correctly share a model, such as a vault HBIM object, one needs to know: which was the commitment purpose and thus the required scale; how it has been surveyed; if the model has been generated in a congruent way, that depends on the object level of complexity and the type of geometrical survey to generate an Object Model with the proper accuracy. Such Information must be included as metadata within the Level of Information, of each object model in order to manage the different Levels of Geometry within the different phases of development of the preservation process and the correct re-use in the data sharing process in the cloud (i.e., throughout Object Libraries).

The 3D object model of the main façade integrated geometry from laser scanning and material documentation by mean of the orthophoto from photogrammetric surveying at the GOA20 scale to read DEM morphology after the earthquake and GOA5 to read the different marble finishing in the different restoration phases in the past connected to different skilled workers capacities (Fig. 7).

#HBIM LOGs-LODs (Level of Geometry and Level of Development): These parameters cross the different phases of the preservation actions and plan by mean of the HBIM, as explained in the following paragraph.

#HBIM WorkBreakdown Structure: HBIM enabled models allows the professionals to connect the WBS plan of activities to the information and models, supporting the metric and costs computations planning all the activities from the preliminary phases to the executive phases.

4.2 Structural Health Monitoring: #Finite Element Analysis Complex Models as a Parameter of Quality (BIM-to-FEA)

#Structural Health Monitoring (BIM-to-FEA). The importance of taking into account all the components within the overall architectural heritage, and their own behaviors, taking in account the materials construction techniques, within Structural Health Monitoring with their characteristics has been illustrated in many kinds of research: it contributed to understanding failures due to long term behavior of heavy structures [15].

In the case of the Basilica di Collemaggio the importance of field failures analysis of the Basilica S. Maria di Collemaggio has been highlighted [16]. Starting from the surveying and on site-analysis, a Finite Element Analysis has been realized using the HBIM Objects model (Fig. 8).

Fig. 6. HBIM of the octagonal columns, the stereotomic analysis of the ashlars embedded in the HBIM, and the restoration with the final result. Courtesy of ABClab-GIcarus (F. Banfi, D. Oreni, R. Brumana)

Fig. 7. HBIM object libraries: a growing open catalog made by all the richness and specificity of the single object model: here the façade concept, the decorations, and the richness of the Rose windows. Courtesy of ABClab-GIcarus (F. Banfi, R. Brumana)

The BIM-to-FEA process has been carried out to get the interoperability and model transformation for the Finite Element Analysis [17]; the model has been obtained taking into account all the structural components as in the case of the HBIM façades objects, the vaults, the HBIM octagonal column with the stone ashlar data and arches, together with the Information coming from the HBIM-DB of the material and decay analysis obtaining the simulations models of the structural behavior.

It contributed to addressing the identification of the design solution for the replacement of the crashed dome and roof with the ancient wooden solutions. Different GOAS has been adopted in the processing tools by the structural engineering research team.

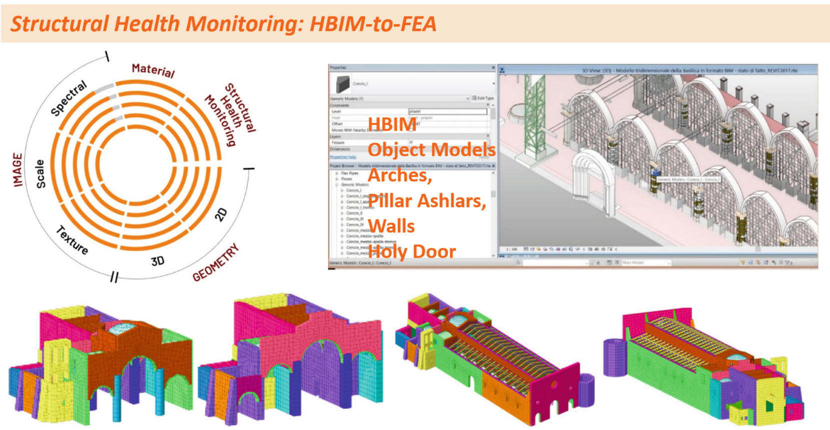

Fig. 8. Structural Health Monitoring: Finite Element Analysis complex models as a parameter of quality (HBIM-to-FEA). Courtesy of ABClab-GIcarus (F. Banfi, A. Franchi, R. Brumana)

4.3 3D Quality Models Enriched by Building Archeology: HBIM 3D Volume Stratigraphic Units and Levels of Uncertainties

#Building Archaeology. Stratigraphic Units detection and 3D volume stratigraphy as a parameter of quality models: 3D volume stratigraphy and building archeology taking into account the relations among the Stratigraphic Units represent a further parameter to describe the quality level of a HBIM, as shown in the Fig. 9 respect the level of Fig. 5. The methodological approach of the so-called building archaeology [18, 19] helps to clarify not just the recognition of the stratigraphic units [20] starting from the material analysis and the decay mapping of the surfaces but also the interdependencies and relations among the different Stratigraphic Units (Fig. 10). As an example 3 different relationships generally symbolized are described as follows:

- Horizontal 'S' symbol which hooks two stratigraphic units: Stratigraphic ratio (relationship among 2 USs): it binds to, corresponding to contemporaneity and proven stratigraphic coherence of two different surface units.
- Underlined arrow symbol that faces one of the two stratigraphic units: Stratigraphic ratio (relationship among 2 USs): leans on…, covers, etc.; symbol applied on the part that covers, leans; indicates a ratio of anteriority /posteriority (the surface with arrows is rear).
- Zigzag underlined symbol: *Breaks/is broken*, *cuts/is cut*, are an example of options applied to the perimeter of the surface that is cut (and therefore pre-existing), and that can be identified by the analysis.

A shift of the 3D quality model toward volume representation represents a further level of degree of complexity that the Building archaeology informative modeling turned into 3D volume stratigraphy can contribute to decoding [21]. It can be applied to the single components, as in the case of facades or vaulted systems [22] to better investigate the result of 3D geometry influenced by the construction techniques and/or the transformation phases. The Scan-to-BIM process has been extended to Building Archaeology informative model to transfer these 3D models augmented by the Information into VR experiences [23]. The methodology has been applied to the 3D stratigraphy of the St. Francesco Church in Arquata del Tronto components (walls, roof, ceiling, flooring), which could be enriched by NDT analysis. Some components of the church (i.e., the façade) were deeper analyzed thanks to Building Archaeology: the Building Archaeology HBIM of the façade embeds the DB on materials and construction techniques, which shows the provenance of the Information in order to make aware of the reliability of the collected data that could come from direct (i.e., on-site observation) or indirect (i.e., archival document) sources. The material and decay DB related to the HBIM was realized according to the Building Archaeology, and each item has its stratigraphic Information, picture, texture drawing, and on-site and historical documentation.. To this aim, a Building Archeology property model devoted to managing the properties related to the 3D Volume stratigraphy have been defined, including a field where to highlight the level of Uncertainty of the relationships among the different transformation phases that occurred in the past, given that not all of them have been clarified.

Informative models can contribute to enriching and feeding VR/AR transferring contents to citizens. The case of AR project developed for the St. Francesco church represents the potentials of virtual-visual storytelling (VVS) allowing users to convey the informative models, including the construction phases, discover tangible and intangible values of the building through interactive virtual objects (IVO).

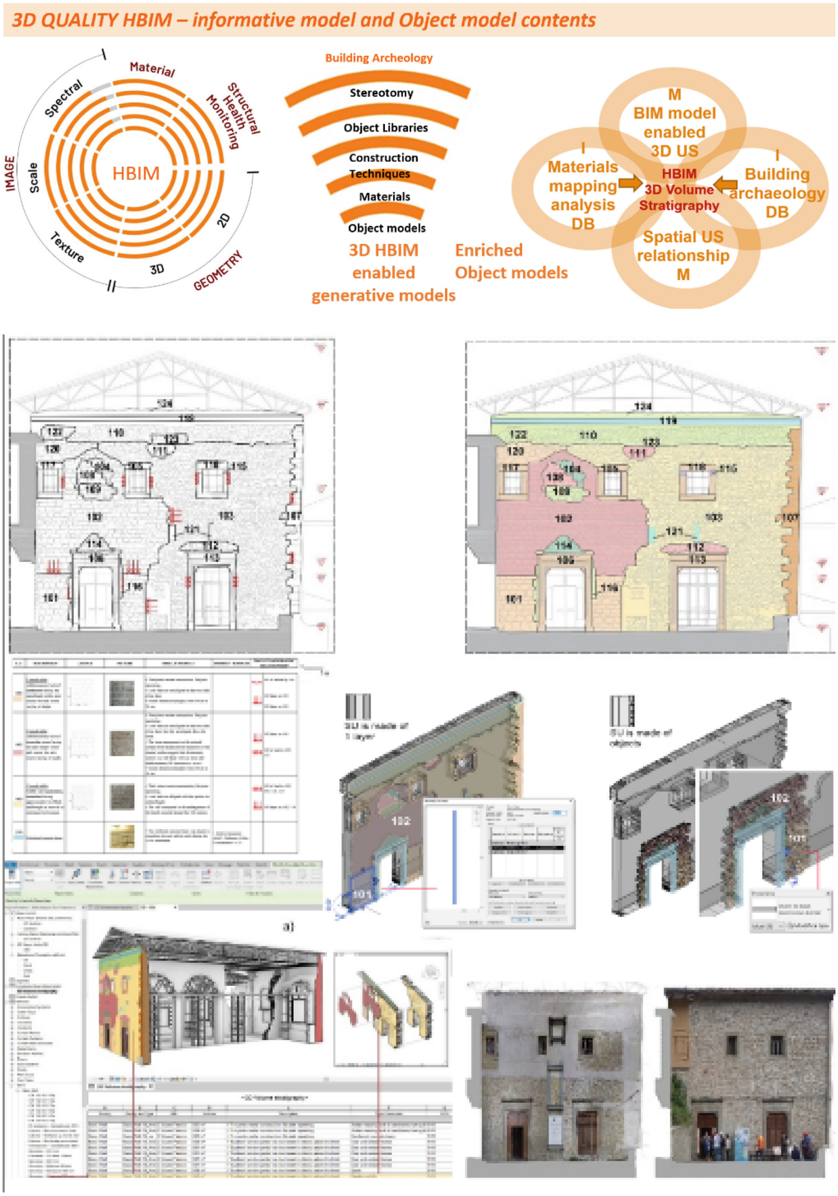

Fig. 9. Building Archaeology informative modeling: 3D volume stratigraphy (St. Francesco Church, Arquata del Tronto after the 2016 earthquake). Courtesy of ABClabGIcarus (F. Banfi, C.Stanga, R. Brumana)

Fig. 10. Toward informative models feeding AR/VR. Courtesy of ABClab-GIcarus (F. Banfi, C.Stanga)

5 Toward Quality Model Specification: BIM to HBIM LOGs-LODs, Reversing the Logic Simplex-to-Complex BIM Model (Building Construction) in Favor of Complex Modeling Knowledge-Creation Since the Design Starting Phases

#HBIM Level of Developments and Levels of Geometry (LODs and LOGs). Informative quality models (as BIM, GIS models) can be gained progressively enriching the Information coming from the different BIM uses (materials, decay analysis, construction techniques, decorations, surfaces finishing, structural behavior, energy performances): they can support the preservation design project and decision-making process till to the life cycle management. LOD and LOG applied to HBIM con be considered parameters to drive HBIM quality models.

In the BIM logic of the building construction, the progression of different LOGs (Level of Geometry) within the LODs (Level of Development of the different phases as the pre-design phase, the design phase till to the facility management) is justified by the progressive enrichment of the geometry and Information connected to the new construction process (LOG-LOD100–500). When turning toward the preservation aims, we have to take into account the specificity requiring since from the starting phase a level of richness and complexity in the HBIM modeling to understand the phenomena and to carry on the assessment.

5.1 # Level of Development Phases Inherited by the BIM Logic and Adapted to the HBIM

BIM LOG/LOD100–200-300–400-500–600 are hereafter adapted to the HBIM specific domain of the architectural heritage. The architectural heritage with all its components requires the maximum effort of knowledge and details since the starting phase to support a decision-making process devoted to proposing sustainable and reliable solutions in the design process and to preserve the heritage subject in the intervention and its maintenance across the time.

LODs-LOGs have been turned as follows:

 # LOD100 (Pre Design): the LOD100 (Pre Design) has been turned to data collection (LOG100 “Conceptual model, historical reports and archives”);
 # LOD200 (Digital documentation phase): it has been added a “Digital documentation phase” (LOD200) to replace the schematic design phase, devoted to the acquisition of the “Appropriate geometry (LOG200)” correspondent to the digital 3D survey and on-site data collection” not present in the current specification nor in the Heritage domain nor in the Infrastructure domain.
 # LOD300 (As-found HBIM model): an “As-found HBIM model” (LOD300) phase obtained by the “Precise Geometry, SCAN-to-BIM model object” (LOG300) devoted to the HBIM modeling phase has been introduced. As previously described, the adoption of one or more scales to model the objects allows professionals to identify the proper scale of each component, function of the contest, geometry, funding, and purposes.
 # LOD400 (Design development – Conservation Plan): the Design Phase has been shifted and adapted to the HBIM uses, thus addressed to the “Conservation Plan” (LOG400).
 # LOD500 (Construction Stage): this phase is simply shifted and tuned to the HBIM construction site, supported by LOG500 “Conservation site”.
 # LOD600 (Facility Management): it is integrated by the LOG600 “As-Built, LLCM, CDE, HUBs”: it implies, as in the BIM logic, the management, monitoring, and communication process from the as-built phase.

5.2 Levels of Geometry Proposal in the Heritage Domain: HBIM LOG100–200-300–400-500–600

 # HBIM Levels of Geometry (LOGs). The proposal to adapt the current LOD-LOG definition – so far adopted for the new building domain - has been introduced to manage the 3D quality model within the conservation process, taking into account each object unicity. The concept of GOAs scales previously defined can be adopted in the function of the different phases and needs in the specific LOGs.

HBIM LODs-LOGs managing the 3Dquality model within the preservation process has been introduced not present in the process as in the following cases (Fig. 11).

The LOG progression is no more related to the scale content defined by the GOA: thus, within each development step, the scale can be defined with respect to the user needs (Fig. 12).

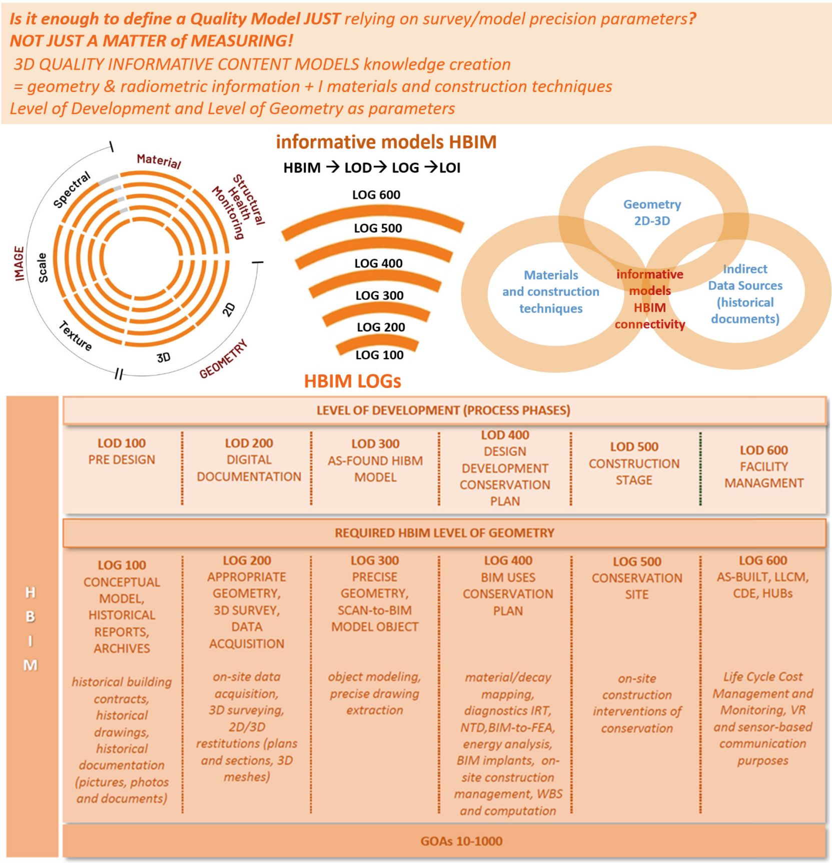

Fig. 11. The proposal of targeted LODs-LOGs adapting the current BIM LODs-LOGs to the HBIM domain. GOAs (models scales) cross all the LOGs, being adopted by the different actors involved in the different phases (LOD200–300-400–500-600). Courtesy of ABClabGIcarus (F. Banfi, R. Brumana, C.Stanga)

The HBIM LOGs has been defined as hereafter proposed:

 # LOG100 - Historical report: it has been introduced to collect the historical drawings, documents from Libraries, Archives, Maps Collection, Open Data Digital Collections (as Europeana), replacing the 'pre-design' concept model;
 # LOG200 - Appropriate geometry: 3D surveying and on-site data acquisition have been introduced within the HBIM LOGs addressed to the surveying to get 2D/3D drawing and mesh digitization, so far totally missed within the BIM logic;
 # LOG300 - Precise geometry: Scan-to-HBIM model Objects generation has been specifically introduced to manage the generative HBIM modeling phase to get HBIM enabled objects, not supported by the mesh or mass models;

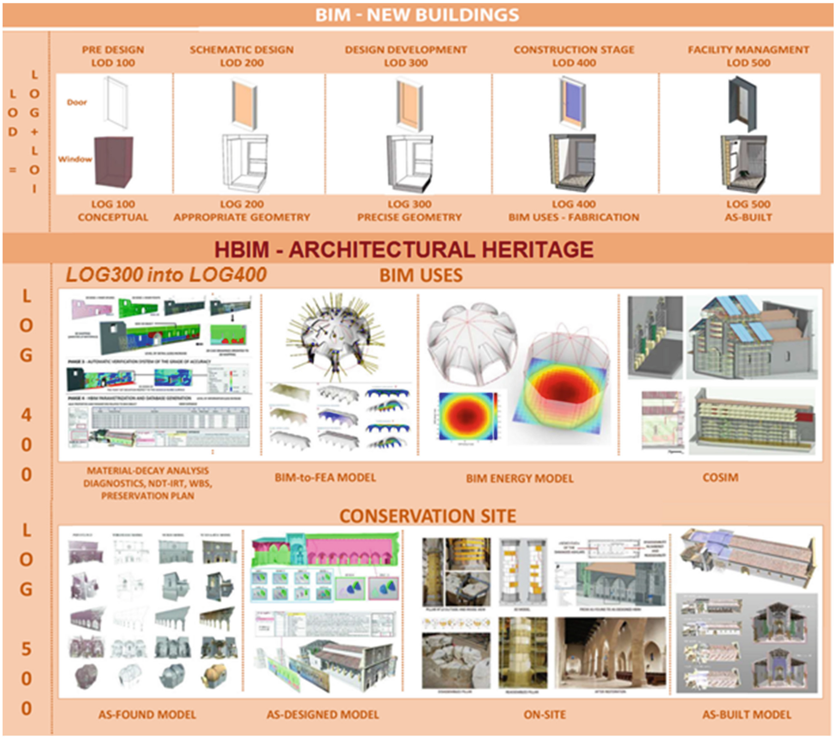

Fig. 12. HBIM turned into preservation aims to support the preservation phases described by the Level of Development (LOD) and the Level of Geometry (LOG): the richness of geometry obtained since from reliable LOD300 (HBIM object model generation – Precise Geometry) supports the LOG400 (HBIM uses) and the Conservation site management (LOG500). Courtesy of ABClabGIcarus (F. Banfi, R. Brumana, C.Stanga)

 # LOG 400 - HBIM uses: HBIM-Uses data management (i.e., preservation plan, inserting the missed material-decay analysis, Work Breakdown Structures- WBS, BIM-to-FEA, or Energy Efficiency analysis); LOG400 manages different scale models (GOA Scale), complex models with high level of accuracy together with simplified model scales. The choice depends on the preservations experts needs but also on tools, as in the case of Energy Efficiency tools requiring so far simplified 3D models;
 # LOG500 - Conservation site: HBIM construction site management (CoSiM), on site interventions of preservations;
 # LOG600 - Facility Management; it has been addressed to manage Long Life Cycle Management (LLCM) starting from the As-Built, within Common Data Environment (CDE).
The richness of reliable quality model geometry obtained since from the starting phase by LOD300 (HBIM object model generation) supports the LOG400 (BIM uses), the preservation site management (LOG500), as shown in the Fig. 13.

5.3 Sharing 3D Quality Models, Re-use and Circulation: Common Data Environment Toward XR Platforms and Interoperability

 # Re-use and models circulations. In the UK, Level 2 is also known as Common Data Environment (CDE) or a 'federated model' where it is possible to use different models to create a digital HUB, giving a complete holistic view of the building.

Assuming that a LOG400 (BIM-uses) can express the concept of model interoperability, it is also useful to consider how this three-dimensional Information can be shared among users. LOG500 and 600 introduce the idea of sharing models through CDE, increasing the level of collaborative communication: HBIM are evolving into interactivity, immersive fruition and interoperability through digital model re-use [23].

In the Digital Cultural Heritage (DCH), archaeological sites, architectural heritage, and infrastructures require the management of different Information previously described. Consequently, in this specific context, it is necessary to underline that CDE should be fed by many data, formats, and models, oriented towards different uses, to improve the management of the Objects over time, allowing different users and operators to access informative models with additional commitment and limitations in the data modifications.

Therefore, the shared data environment (CDE) should be considered a multi-access to multi-source information used to collect, manage, and share graphical models with non-graphical data in conventional data formats evolving toward XR platform to support AR/VR informative models [24]. According to PAS 1192–2: 2013, a CDE may use a project server, an extranet, a file-based retrieval system, or other suitable toolsets.

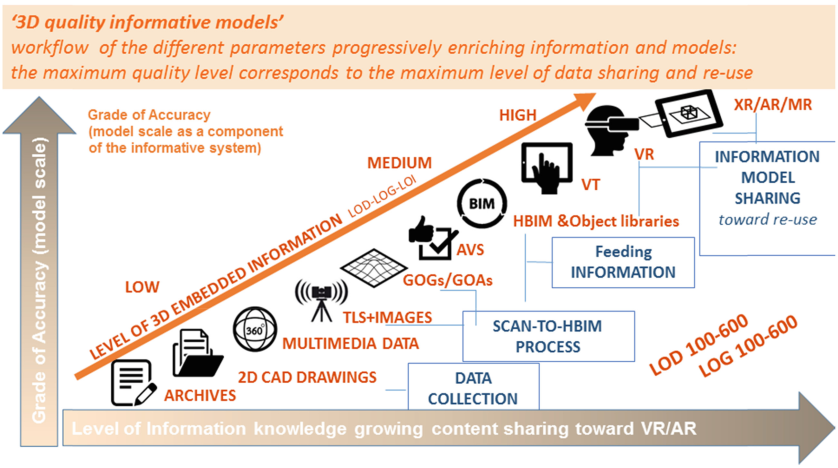

Fig. 13. 3D quality informative models possible workflow: managing different parameters and progressively enriching information and documents from digitization to XR experiences. Courtesy of ABClabGIcarus (F. Banfi, R. Brumana)

6 Conclusions and Remarks

Quality driven models allow a progressively increasing of knowledge creation, opening the doors of informed communication using co-working spaces, common data environment, and geospatial hubs with linked informative model objects (as HBIM), in the form of Linked Open Data (LOD), enriching and augmenting reality also by using VR/AR/MR. Therefore, it requires CDE and platform capable of digesting models progressively enriched by the information supporting eXtended Reality experiences. The re-use requires to foster common languages for data exchange and vocabularies, taking into account the richness and specificity of the construction techniques and of the information linked to the HBIM. It also requires filling the gap of lack of skills boosting capacity building, especially in the modeling phase growing DG content skills and in the use of HBIM by the experts.

A multi-parameters radar chart application can be implemented to better support the users in the decision-making during the 3D quality model generation helping measure the level gained during the process.

Standardization and ad hoc guidelines addressing the complexity of cultural heritage, as in the case of LOD-LOG-GOA definition in the HBIM, can contribute to avoiding misunderstanding and misuses in the re-use and circulation of the 3D model libraries and sites.

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