Building Information Modelling – A Novel Parametric Modeling Approach Based on 3D Surveys of Historic Architecture

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Abstract. Building Information Modelling (BIM) appears to be the best answer to simplify the traditional process of design, construction, management and maintenance. On the other hand, the intricate reality of the built heritage and the growing need to represent the actual geometry using 3D models collide with the new paradigms of complexity and accuracy, opening a novel operative perspective for restoration and conservation. The management of complexity through BIM requires a new management approach focused on the development of improve the environmental impact cost, reduction and increase in productivity and efficiency the Architecture, Engineering and Construction (AEC) Industry. This structure is quantifiable in morphological and typical terms by establishing levels of development and detail (LoDs) and changes of direction (ReversLoDs) to support the different stages of life cycle (LCM). Starting from different experiences in the field of HBIM, this research work proposes a dynamic parametric modeling approach that involves the use of laser scanning, photogrammetric data and advanced modelling for HBIM.

Keywords: BIM · Complexity · LoD · NURBS · Point clouds

1 Introduction

The innovation and development of Information Communication Technology (ICT) in support of the Architecture, Engineering industry, Construction and Operations (AECO) is characterized by the growing use of BIM [9, 12].

The digitized management of historic buildings, infrastructure and complex systems bases its foundation on theoretical and operational processes in continuous development. In this process, the level of transmissibility of knowledge is fragmented and not fully assimilated by the professionals involved. Their software and support tools are not able to accommodate the correct level of complexity causing the generation of simplified 3D models (not corresponding to the as-built) or complex BIM for a subsequent management.

Research and introduction of new paradigms as complexity for the built heritage is a basic need to develop operative aspects to support identification, assimilation and

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transmission of useful and valuable information for the preservation of cultural heritage [2, 7]. Each application requires geometric and technical characteristics defined by advanced modeling procedures that could lead to data loss if not property tuned. Nowadays, modeling requires long generative practices and specific computer skills that correctly interpret the complexity of the buildings, and then transmit them within an operating process that consists of different interdisciplinary teams [3, 5].

The complexity is a fundamental prerogative for high transmissibility of the information [10]. It results essential to enhance the vast number of technical analyses for all types of buildings [1, 14]. It can become a definable standard parameter addressed to European and global directives for the next years in favor of BIM integration in design and construction processes.

The objectives of this research are:

- Integrate 3D survey techniques and advanced parametric modelling, providing a real starting point for the creation of as-built BIMs with different LoDs.
- Argue the usefulness of a methodological advanced modelling approach that automates the generative process of HBIM favouring the control, management and transmissibility of the information collected during the building's life cycle.
- Show how BIM can support the process of designing, building, restructuring, maintenance and analyses, through three case studies aimed at different ReversLoDs approach for historic buildings.
- To discuss, analyse, identify gaps in the work carried out, and propose possible future research lines.

The process is based on research work carried out in recent years in the field of HBIMs of great historical value buildings in the Italian territory. It was supported by public institutions, multinational companies and research groups that have made possible a sensitive scientific growth in the protection of architectural heritage. The Italian case studies which will be described are the Basilica of Collemaggio in L'Aquila, Castel Masegra in Sondrio and finally the Azzone Visconti Bridge in Lecco. The chronologic order imposed in this paper follows the creation of models, from oldest to most current BIM, in order to highlight the improvement of the interchangeability with different LoDs obtained from 2013 to 2016.

2 A Novel Parametric Modeling Approach

This research proposes a dynamic methodological approach based on the management of complex 3D shapes managed and manipulated with a new initial LoDs obtained from the 3D survey and with bidirectional levels of complexity (ReversLods) which provides the integration of NURBS modeling and parametric applications to support life cycle management (LCM). HBIM increased the level of knowledge of the building through the integrated use of various applications, which can be mainly divided into two macro families: pure modeling software like MC Neel® Rhinoceros, and Autodesk® Autocad 3DS MAX, which are able to fully investigate the morphological appearance of the building, and BIM Platforms such as Autodesk® Revit and ArchiCAD Graphisoft®, where the typological differentiation and the ability to associate additional information is the basic logic. The first family is characterized by a free modeling approach that generates 3D elements and surfaces able to reproduce complex forms. The user can create surfaces and solids starting from the basic generative elements like lines, NURBS (Non Uniform Basis Splines) [11], and mesh [16]. The disadvantage is the absence of tools that allow the parameterization of the elements. The second family is characterized instead by an internal structure made up of a database with families of objects. These objects represent the architectural elements that form a building. Each element is adjustable in its sub components, the parameterization of the dimensional components can be adjusted and the type of each element can be edited through the use of settable parameters (before and after) [6]. The main disadvantage that impedes the use of BIM for historic buildings is the modeling of complex shapes: only through hard, long and complex modeling practices it is possible to reach a sufficient level of detail. In historic buildings morphological and typological aspects are not aligned. This is a fundamental problem for the creation of HBIMs derived from 3D surveying techniques. The interoperability of modeling software is a crucial aspect in order to optimize the peculiarities of the two modeling families.

The transition from pure modeling software like Rhinoceros, AutoCAD to Revit depended on the determination of the complexity and the level of accuracy of BIM. Modeling must adapted to the information collected during the survey, allowing the association of data to 3D parametric objects [4]. The advantage of combining these two macro families with a survey based laser scanner (*integration*) could develop new methodological approaches to investigate the accuracy of existing assets and the overall control over the entire design process as well as construction, maintenance of building (Fig. 1).

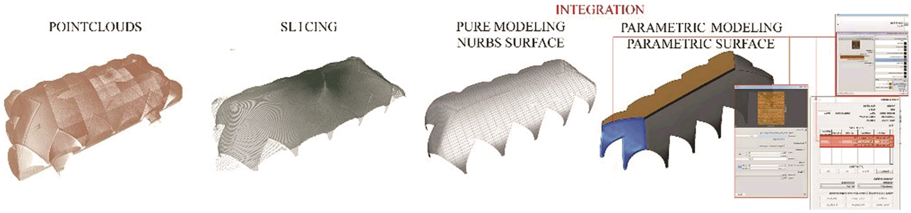

Fig. 1. Generation process characterized by the integration of pure modeling (NURBS) with the parametric modeling in BIM application.

For this reason, the 3D model must guarantee in terms of morphological features and reality and then know how to steer a specific LoD [8]. The peculiarities of an existing building, complex shapes of architectural and structural elements can be properly interpreted, generated and represented by generative advanced modeling tools based on NURBS technology.

The technological advancement requires continuous adaptation of the various standards. In recent years, new parameters have been defined to assess the level of the 3D model in geometrical terms and its associated information.

The management of CAD formats presupposes a development of interoperability techniques to convey the totality of information available. This integration requires an orientation of the models based on different LoDs of BIM, guaranteeing the new hierarchy of the model. This means that the use of the information associated with the parametric model determines level of transmissibility of information of the building. Consequently, transmission of knowledge is determined by the modeling of each element and by the level of complexity transmitted during the process. Figure 2 shows the integration process used to generate HBIM.

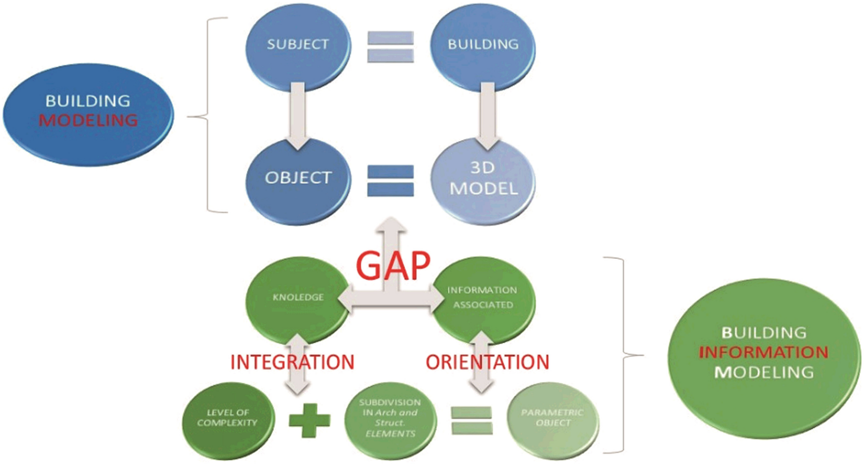

Fig. 2. The proposed parametric modeling approach – integration of pure and parametric modeling in order to improve the transmission of complexity, information and knowledge of the building

3 LoD Level of Development and Detail

LoDs allow us to measure the reliability and security of information associated to the BIM during the building process: starting from planning and construction to maintenance [8]. From an operational point of view, the advantages in the built environment can be substantial especially in terms of time in the implementation phase of the 3D model. LoDs are divided into a first ‘not modeled’ Conceptual representation (100), a second level with the general requirements and the main quantities (200), a third level to support the detailed design, a fourth level ‘manufacture/install’ in support of construction planning (400), and a fifth and final level ‘as-built’ in support of a Asset management (500).

In most cases, a 300-definition level can be a good initial compromise to manage a new building. It is possible to pass to the next levels following the requirements of the design and the following integration in the building process. It is sometimes impossible to define a correct LoD for existing and historic buildings. For example: the use of a laser scanner does not allow the automatic recognition of materials and elements.

On the other hand, the protection and conservation of the built heritage requires, (during the survey) to use non-invasive methodologies. The use of destructive techniques, such as core drilling, is not permitted in order to protect the building. Therefore, the materials used and the construction techniques are unknown in the early stages of laser scanner survey. The survey of the building can reveal morphological and typological aspects even after years. However it is sometimes necessary to decrease the level of definition of the model obtained, reversing the accuracy of the model to support the design process. Consequently, it is not possible to define a clear LoD during the initial agreement between BIM developer and customer; therefore the model will consist of elements with different LoDs. This should require a further phase of definition of not-modeled objects. The transmission clearly implies a duty to report the deficiencies of the model in terms of quality and quantity.

The following case studies show the need to integrate different LoD in the generation phase of the models to support the process and the importance of advanced modeling that requires to invert the level of modelling (ReverseLoDs) for specific parts/components of the building.

4 BIM Process: Development and Management

The proposed method is composed at different operative steps that required different types of model. Modelling has to guarantee different sub-models starting from the same model with different levels of precision, accuracy, definition and development (Fig. 3).

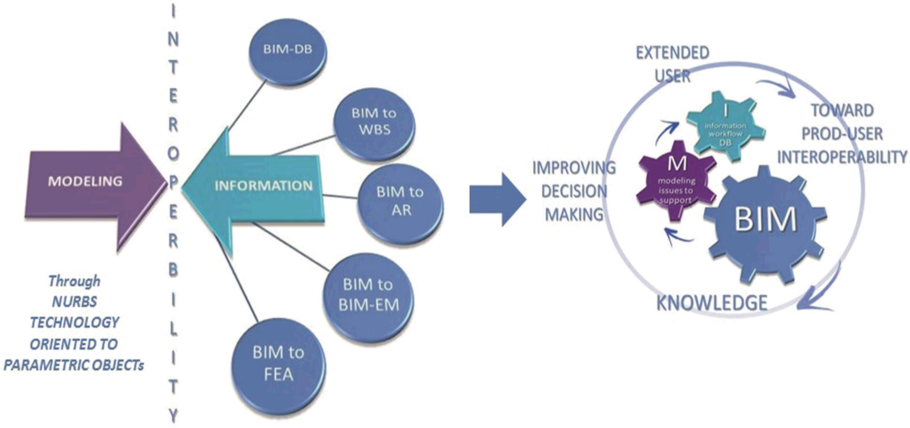

Fig. 3. Orientation model based on the integration of advanced modeling to improve the transferability of knowledge in BIM

The generation of complex elements such as vaults, arches, domes and walls damaged capable of represent the laser data requires complex modeling practices.

Figure 4 describes the process in its analytic and operative phases. It shows the required model and the ReverseLoDs approach:

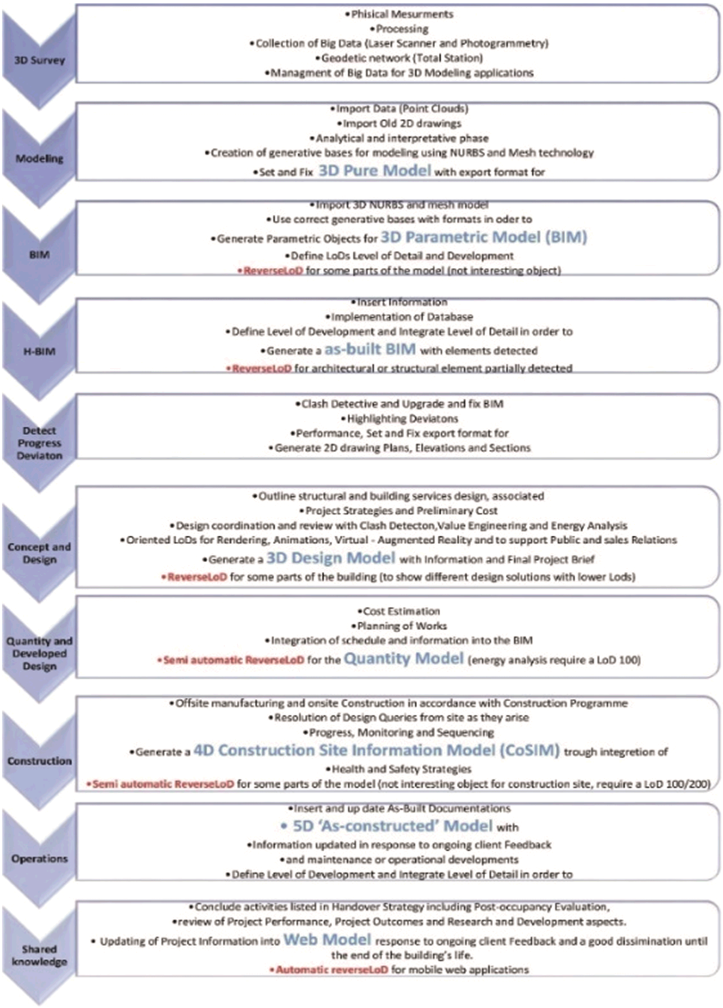

Fig. 4. BIM Implementation: different type of model in life cycle

The key idea is based on both interoperability and integrated use of development levels, as well as definition (for each building) should be targeted of specific analyses. The analysis software must be viewed from the point of view of an advanced modelling practice, that is a constraint in which the first modeling step must be oriented to the correct reading of the BIM. It must to update and change throughout the process and this requires an improvement of knowledge of the modeling techniques. This requires a model that must allow an increase or decrease (ReverseLoD) in the level of complexity. The new paradigm of Orientation of model/modelling is crucial to achieve such particular type of analyses [15].

5 Case Study 1: Bidirectional Generative Process to Support the Restoration Project of Basilica of Collemaggio in L'Aquila

In 2009 the Aquila's earthquake severely damaged the apse of the basilica, leading to the collapse of the roof. The pillar of the transept completely collapsed. Their supported the weight of the vault and the covering system. Naves have suffered subsidence in the north wall (out of plumb of about 40 cm) and in the pillars. This case study shows that the levels used in the model are different because they had to support different phases of the restoration project. Specifically, the generative phase resulted in an HBIM and its use in the restoration project, with a special attention to procedures used to preserve the complexity of photogrammetry and laser scanning data and not always suit the design phase. The 3D survey of the basilica required integration of detection techniques (Fig. 5) that could restore the morphological complexity of the construction.

Fig. 5. 3D survey campaign with UAV, total station and laser scanner 3D

The geodetic network was measured with a Leica® TS30 total station, with a level of precision on the measurement of 0.6 mm and 0.15 mgon on measures of azimuth and zenith angles. The number of scans was 182 collected, with a resolution of 44 million points. The UAV survey with Astec Falcon 8 equipped with RGB camera Sony NEX - 5N photogrammetrically calibrated performed have allowed us to use a powerful tool to inspect the condition of the roof in 2013, providing useful data for the generation of as-built model of the basilica.

The morphological complexity of the Basilica was the key to refine modelling techniques oriented to the generation of a BIM that represent the actual reality of the building adapted to project requirements. The main objective was to define a high level of detail of the constructive elements of the basilica and achieve an accuracy of modeling with parametric surfaces and objects with a LoD 500. The architectural elements generated from point clouds were characterized obtaining semi-automatic generative profiles through the integrated use of software McNeel® Rhinoceros and plug-in Pointools. This is a support for managing and editing the clouds to proceed to the realization of 2D drawings (plans, elevations and sections) and then the model. Figure 6 shows the generation process: the slice extraction procedure from point clouds led automatic generation of NURBS surfaces and solids. They were obtained by a preliminary morphological quantification corresponding to a LoD 300.

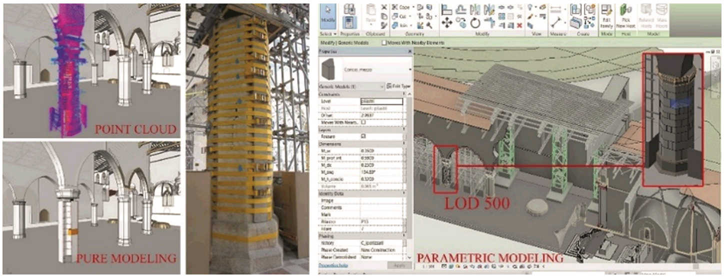

Fig. 6. Generative process. From pointclouds to 3D model the pillars defined by each single stone. The HBIM reaches LoD 500

The flexibility of the method, has allowed transferring each element generated with the pure modeling at a LoD 400, except the excavations, cellars and external parts still characterized by a LoD 200 for a lack of data on the environments, resulting in a lack of thickness of the walls and only a 3D generation of intrados surfaces. Starting from the use of Autodesk® Revit, the HBIM of the Basilica was able to associate useful information to the next steps. Direct survey was essential to determine each sub stone form. Each pillar is composed of a certain number of courses; each course is composed of a variable number of stone blocks (Fig. 6). The definition of the laser scanner survey did not allow detecting the joints of connections of the various segments because of the safety straps covering each pillar, so the direct survey allowed migrating the main geometric information of the blocks in the HBIM with LoD 500.

Subsequently, the level of definition achieved exceeded the real needs for the Construction Site (4D) of this phase [13]. The simplification required a LoD 200/300/400.

Finally, the flexibility of the 3D model allowed the updating of the project requests in the preliminary and final phase thanks to 3D rendering and digital video simulations generated with the application Abvent® Artlantis. As shown in Fig. 7,

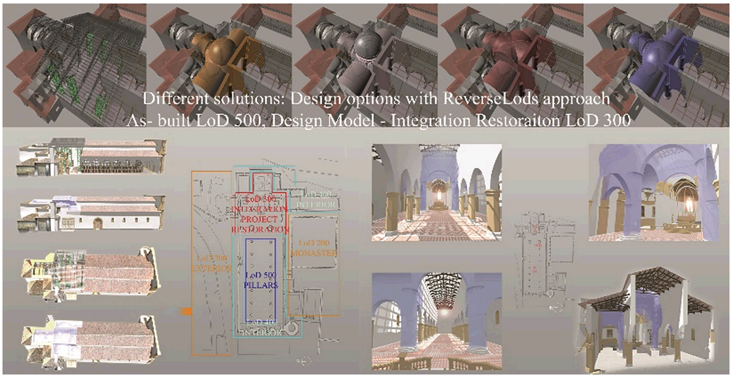

Fig. 7. Comparing as/built and project. Through different LoDs it was possible to integrate BIM (LoD 500) with 3D design integration of the Basilica with a LoD 300.

through ReverseLods it was possible to integrate design assumptions (LoD 300) to LoD 500 (as-built) of the basilica, supporting the design choices during life cycle of project restoration.

6 Case Study 2: Modelling, NURBS-Mesh Technology, LoDs and HBIM of Masegra Castel in Sondrio

This case study involved the construction of a HBIM of Castel Masegra in Sondrio by laser scanner and photogrammetric data. The objective of this project is to preserve the architectural and landscape heritage of Valtellina and Valposchiavo, sharing activities, knowledge and methodologies using the most advanced techniques for diagnostics, restoration, maintenance and management of cultural heritage, which were developed by interpreting the preservation as a long-term process. The 3D survey has produced 176 scans for a total of 7.5 Billion of points with a resolution greater than 3 mm by using a Faro® Laser Scanner Focus 3D and Leica® TS30 total station. Each scan was composed of 44 million points. A robust geodetic network controlled the large amount of data collected with laser scanner.

The modeling phase is based on a generative approach of the various elements surveyed with the laser scanner. The integrated use of Autodesk® AutoCAD and McNeel® Rhinoceros allowed us to generate 3D profiles for the generation of NURBS surfaces able to follow the clouds of points with an average deviation of around 2, 3 mm. Specific tools for point cloud management were recently included in AutoCAD2015. The integrated use of the Pointools plugin in McNeel® Rhinoceros and Autodesk® ReCap have greatly shortened the generative process of the model. Cloud management was carried out through the new .rcp format, which can index and group all the scans. New cleaning tools of point clouds have determined the area of interest directly in AutoCAD, without using other plugins. The case study of the umbrella vault at the second floor exploited the entire method applied to the Basilica of Collemaggio (Fig. 8).

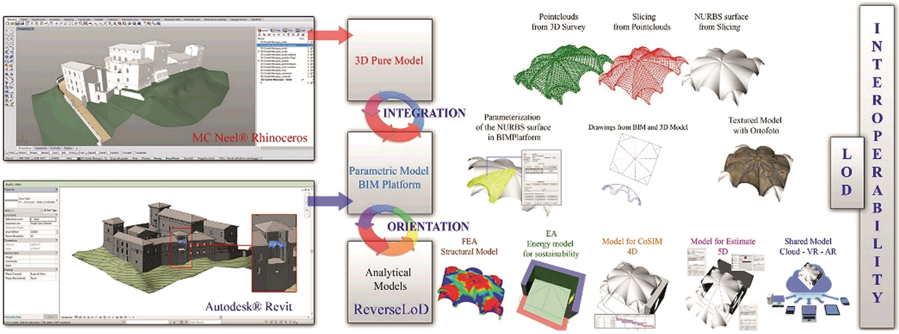

Fig. 8. Modeling process – integration, orientation, LoD and interoperability of 3D model

The combined use of laser scanning data and Agisoft® PhotoScan gave an orthophoto that highlights the morphological complexity of the vault. It was generated by the alignment of 34 photos and a total of 95110 points. The use of a total station allowed to define 9 control points and correctly georeferenced the photogrammetric model with the laser point clouds. The integration of these two techniques allowed us to reprocess data collected directly in Rhinoceros and model the data by importing the mesh generated in Agisoft® PhotoScan through the obj file format. Through this format all the information can be listed for the definition of lines, polygons and curves and complex surfaces. 3D mesh generation led to determine a number of profiles and control sections of the complex geometry of the vault in McNeel® Rhinoceros. To avoid possible geometrical deviations, each profile was used with the ReverseLoDs approach, for the next portion of the vaults.

Thanks to the dynamic offset, it was possible to automatically parameterize surfaces with a LoD 400. Figure 9 describes the modelling process used: the transformation of wall surfaces allowed the integration of physical information, for materials with LoD 500 and the orientation the model for different analyses.

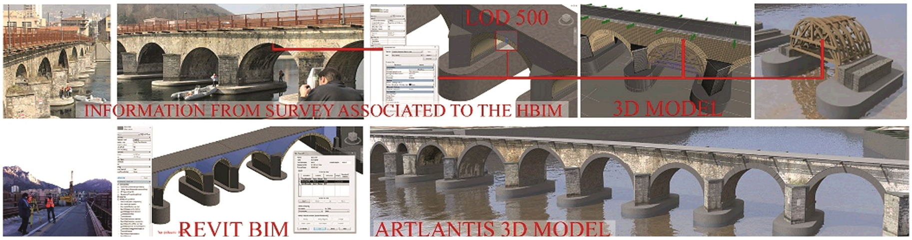

Fig. 9. From 3D survey to BIM LoD 500 and an example of historical rib

7 Case Study 3: LoD 500 for Defining the HBIM of a Mediaeval Infrastructure - Visconti Bridge in Lecco, Italy

The third case study is the HBIM of the medieval bridge Azzone Visconti in Lecco. This is still under investigation by the public administration of the town of Lecco. The main objective of the research was to create a model that can accommodate the maximum amount of information collected by other research groups (geologists, structural engineers, historians etc.) to monitor and preserve the bridge.

The survey campaign involved the generation of a geodetic network of 77 scans obtained with a Faro Focus 3D. The total number of laser scanning points was more than 2.5 billions, with an average precision of ±3 mm achieved by using chessboard targets detected with the total station and additional scan-to-scan correspondence (spherical targets). Photogrammetry has allowed the realization of number orthophotos of the 11 arches of the bridge and its fronts.

The purpose of modeling was to achieve a LoD 500 and implement the method of the two cases previous studies. The scans of the bridge have been transferred directly into the Mc Neel® Rhinoceros. The NURBS technology (due to its ability to interpolate points) allowed us, to generate surfaces that follow the data laser without geometric deviations. The creation of the wall partitions in Autodesk® Revit carried out through the automatic parameterization of the NURBS surfaces using the tools Wall By Face and Edit Profile. Thanks to the resolution of the point clouds has been possible to get an example of historical rib with LoD500. The putlog hole have determined the thickness of the various wooden elements of the rib. With the 3D Augmented app you can directly simulate the insertion of the rib on the river bridge.

A comprehensive database (LoD 500) for objects and share information for portable devices was created with Autodesk® A360. Finally, Abvent® Artlantis and iVisit 3D allowed us to created a virtual simulation of the medieval system of construction. The transmission of information to structural engineers, geologists and supervisors can take place by importing the whole model in a cloud service with the automatic ReverseLoDs approach at the level 500.

8 Results and Discussion

The HBIM the Basilica of Collemaggio can directly demonstrate the general complexity of geometric model through different LoDs, which avoids simplified representations that do not match the actual complexity of the building. In the Concept and Design phase the model can receive changes in certain areas of the building to support different design solutions. The inversion of LoDs of these areas can be useful for modelling practices in terms of time and design simulations at lower or higher levels.

The modellative practices of Castel Masegra have been optimized trying to reduce processing time, costs related to the generation of the model and increase its level of interoperability for the next maturity level. Starting on the experience of the Basilica of Collemaggio, it was useful to set a proper general LoDs. The large size of an HBIM required ReverseLoDs practices to guide the extrados and intrados surfaces of the vaults.

The HBIM model of Visconti Bridge showed the morphological features of a medieval infrastructure bypassing the generative phase of 2D drawings, thanks to a LoD 500 supporting the entire decision-making process, facilitated the sharing of information in different interdisciplinary groups for the protection and preservation of a historical bridge. Shared knowledge phase provides a process of simplification of the model for mobile devices and clouds in the web. The reversal definition ‘ReverseLoDs’ may provide a selection of the information shared to improve the size of the model, the navigation and its simulation.

9 Conclusion

Thanks to laser scanning technology for a modeler is easier to reconstruct the complexity of the building. Simplifications of the model based on personal interpretive logic is still mandatory of complex projects. This paper presents an advanced modeling technique for historic buildings, which integrate the pure modelling and NURBS technology with additional parametrization to orientate the models to the correct level of complexity. The levels of development for the HBIM must ensure a bidirectionality in favor of updates of the constructive elements of the building realized in digital environment for different types of analyses. The ReversLoDs approach for historic buildings can support the process of designing, building, restructuring, maintenance and analyses.

Finally, these techniques highlight the need to introduce a hierarchy of new levels of accuracy of HBIM models giving a certified quality value of the generated model.

References

1. Azhar, S., Brown, J., Farooqui, R.: BIM-based sustainability analysis: an evaluation of building performance analysis software. In: Proceedings of the 45th ASC Annual Conference, Gainesville, Florida (2009)
2. Barazzetti, L.: Parametric as-built model generation of complex shapes from point clouds. Adv. Eng. Inform. **30**, 298–311 (2016)
3. Barazzetti, L., Banfi, F., Brumana, R., Gusmeroli, G., Oreni, D., Previtali, M., Roncoroni, F., Schiantarelli, G.: BIM from laser clouds and finite element analysis: combining structural analysis and geometric complexity. In: International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. 40(5/W4), pp. 345–350 (2015)
4. Barazzetti, L., Banfi, F., Brumana, R., Previtali, M.: Creation of parametric BIM objects from point clouds using nurbs. Photogramm. Rec. **30**(152), 339–362 (2015)
5. Brumana, R., Oreni, D., Cuca, B., Binda, L., Condoleo, P., Triggiani, M.: Strategy for integrated surveying techniques finalized to interpretive models in a byzantine church, Mesopotam, Albania. Int. J. Archit. Heritage **8**, 886–924 (2014)
6. Eastman, C., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, 2nd edn. Wiley, Hoboken (2011). 626 pages
7. Fai, S., Graham, K., Duckworth, T., Wood, A.: Building information modelling and heritage documentation. In: XXIII CIPA International Symposium, Prague, Czech Republic (2011)
8. Fai, S., Rafeiro, J.: Establishing an appropriate level of detail (LoD) for a building information model (BIM) – West Block, Parliament Hill, Ottawa, Canada. ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. **2**(5), 123–130 (2014)
9. Johnson, R.E., Clayton, M.J.: The impact of information technology in design and construction: the owner's perspective. Autom. Constr. **8**(1), 3–14 (1998)
10. Oreni, D., Brumana, R., Banfi, F., Bertola, L., Barazzetti, L., Cuca, B., Previtali, M., Roncoroni, F.: Beyond crude 3D models: from point clouds to historical building information modeling via NURBS. In: Ioannides, M., Magnenat-Thalmann, N., Fink, E., Žarnić, R., Yen, A.-Y., Quak, E. (eds.) EuroMed 2014. LNCS, vol. 8740, pp. 166–175. Springer, Heidelberg (2014). doi:10.1007/978-3-319-13695-0_16
11. Piegl, L.A., Tiller, W.: The NURBS Book. Monographs in Visual Communication. Springer, Heidelberg (1997). 646 pages
12. Succar, B.: Building information modelling framework: a research and delivery foundation for industry stakeholders. Autom. Costr. **3**, 357–375 (2009)
13. Trani, M., Cassano, M., Todaro, B., Bossi, B.: BIM level of detail for construction site design. In: 4th Creative Construction Conference, Krakow, Poland (2015)
14. Aravici, Y.: Towards building information modelling for existing structures. Struct. Surv. **26**, 210–222 (2008)
15. Zhanga, J.P., Hub, Z.Z.: BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies. Autom. Constr. **20**(2), 155–166 (2011)
16. Zvietcovich, F., Castañeda, B., Perucchio, R.S., Morales, R., Uceda, S.: A methodology for updating 3D solid models of complex monumental structures based on local point-based meshes. In: 1st International Congress on Digital Heritage, DigitalHeritage, Marseille, France (2013)