CRITICAL ISSUES AND KEY POINTS FROM THE SURVEY TO THE CREATION OF THE HISTORICAL BUILDING INFORMATION MODEL: THE CASE OF SANTO STEFANO BASILICA

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ABSTRACT:

The new era of designing in architecture and civil engineering applications lies in the Building Information Modeling (BIM) approach, based on a 3D geometric model including a 3D database. This is easier for new constructions whereas, when dealing with existing buildings, the creation of the BIM is based on the accurate knowledge of the as-built construction. Such a condition is allowed by a 3D survey, often carried out with laser scanning technology or modern photogrammetry, which are able to guarantee an adequate points cloud in terms of resolution and completeness by balancing both time consuming and costs with respect to the request of final accuracy. The BIM approach for existing buildings and even more for historical buildings is not yet a well known and deeply discussed process. There are still several choices to be addressed in the process from the survey to the model and critical issues to be discussed in the modeling step, particularly when dealing with unconventional elements such as deformed geometries or historical elements.
The paper describes a comprehensive workflow that goes through the survey and the modeling, allowing to focus on critical issues and key points to obtain a reliable BIM of an existing monument. The case study employed to illustrate the workflow is the Basilica of St. Stefano in Bologna (Italy), a large monumental complex with great religious, historical and architectural assets.

1. INTRODUCTION

The Building Information Modeling (BIM) approach for the design of new projects both in civil and industrial applications is a modern strategy applied since the concept of new constructions (Smith and Tardif, 2009; Eastman et al., 2011; Azhar, 2011; Kim et al., 2013). In these scenarios the design process is no more carried out with two-dimensional (2D) tools but it is based on three-dimensional (3D) elements which are coupled to metadata and additional information. By this way, the new era of designing is based on a 3D model with a 3D database (Aish, 1986; Van Nederveen and Tolman, 1992; Mitchell and McCullough, 1995; Autodesk, 2002). Even if the final product is ideally always the same, when dealing with existing buildings, the creation of the BIM is based on the accurate knowledge of the as-built construction. Such a condition is allowed by a survey that collects those 3D information that will be then used to model in a three-dimensional way each architectural/structural element composing the building under investigation. The richness of the model in terms of both geometry and further information depends on the required Level of Development (LOD) (BIM Forum, 2016).
The BIM approach for existing buildings and even more for historical buildings is not yet a well known and deeply discussed process. There are still several choices to be addressed in the process from the survey to the model and critical issues to be discussed in the modeling step, particularly when dealing with unconventional elements (De Luca et al., 2006; Apollonio et al., 2012; Santagati and Turco, 2017). Moreover, the regulations and the definition of standard data formats as well as standard procedures and standards skills for reference technicians are under discussion both in the Italian (www.uni.com) and in the international panorama (www.iso.org). Concerning the whole BIM approach, the European regulatory framework is rather confused. During the past years, the British and the American experiences were the only terms of reference whereas, since the beginning of 2017, a significant part of the so called UNI 11337 has been approved. This regulation specifically governs the introduction of BIM in the Italian context. Since now, indeed, a tangible experience related to the BIM application in the real professional Italian world is rather uncommon but positive circumstances are now growing to stimulate a quick and solid diffusion of the BIM approach.
The BIM approach is quickly gaining in popularity and promises to change the construction, engineering and architecture industries forever thanks to the suitability in managing existing buildings and the efficiency for revamping and restoration (RIBA Enterprises, 2016; McGraw Hill Construction, 2014). Unfortunately, there are no regulations directly and comprehensively dealing with the topics of surveying methods and data processing strategies to provide a starting point for the BIM process. The availability of new digital technologies for data collection such as laser scanning, image-based approaches, multi-spectral sensors and so on, requires the development of a definite method for data management and data treatment to be properly included into the BIM process workflow in order to optimize the usefulness of the required information (Murphy et al., 2013; Garagnani, 2013; Garagnani, 2015). The main goal of this manuscript is,

therefore, to propose a set of applicable methods and approaches in the ordinary work that will hopefully be useful to stimulate the definition of common reference standards.

The paper focuses on cultural heritage applications and enhances the role of an adequate knowledge of the state of the art in order to provide an accurate 3D documentation and representation. The paper also strongly contributes to identify a comprehensive workflow that goes through the survey and the modeling by highlighting both critical issues and key points that allow obtaining a good final BIM of an existing monument. The need to accurately and fully know the as-built of a building with all the architectural / structural changes experienced over time is indeed crucial for all who are deputed to the protection and conservation of the heritage with the aim of monitoring the evolution of the monument, of designing interventions for consolidation and restoration as well as of correctly scheduling and managing the maintenance. The BIM approach, namely Historical BIM (H-BIM) when cultural heritage is the subject, is particularly suitable to improve the effectiveness and the efficiency of the heritage management during the whole life of the monument (Saygi et al., 2013; Baik et al., 2015). The activities workflow is implemented on a valuable case study, the Basilica of St. Stefano in Bologna (Italy), a large monumental complex with great religious, historical and architectural assets.

2. THE METHODOLOGY

When dealing with existing buildings, the production of a BIM that is suitable to follow the requirements of accuracy, scale representation and LOD provided by the owner or the manager of the building is a crucial point. All the analysis, the interventions and the activities that will be designed and planned in the future life of the building are based on such a BIM and the suitability as well as the reliability of the final product is essential to guarantee the effectiveness and the efficiency that this approach promises. Within this mindset, the surveying as well as the modeling are crucial steps for the success of the process.

The methodology, shown in Figure 1, is outlined by steps in order to highlight the most critical issues to take into account:

1. Integrated survey technologies, such as laser scanning and modern photogrammetry, require to choose the proper instruments paying also attention to their integration. The laser scanner needs to balance resolution and precision with speed capabilities; moreover the presence of the internal dual-axis compensator, which allows to adjust for the identification of precise verticality (Castagnetti et al., 2012; Capra et al., 2015), is also crucial. Referring to the highest portions or in case of big extension, laser scanning is successfully integrated by the new technologies based on aerial image collection and processing, that allow to obtain a 3D point cloud thanks to the modern photogrammetry algorithms (Gaiani et al., 2016; Menna et al., 2016). In this case, the choice concerns the camera, in order to capture images with an adequate quality with respect to the final BIM scale representation, and the UAV (Unmanned Aerial Vehicle) that needs to be able to support the payload balancing the battery duration.
2. Design of the survey that lies in defining the scanning locations (full coverage of the building and low incidence angles by means of ground and top locations), the alignment strategy (eventually targets installation) and acquisition parameters (adequate resolution based on the final required LOD in order to optimize the computational burden of both processing and modeling steps). Concerning the integration with the UAV survey, the design consists in defining the waypoint locations for capturing the images and the flight distance from the object on the basis of the camera sensor type and the expected final pixel resolution.
3. Laser scanner data processing based on noise removal and alignment of all scans within the same coordinate system. Concerning the UAV survey, image processing based on *Structure from Motion* algorithms (Ullman, 1979) is performed to obtain a 3D point cloud of highest part of the complex to be integrated to the laser scanner-based one, thus providing a final comprehensive 3D model.
4. Verification of the 3D point cloud reliability thanks to independent technologies able to guarantee accurate terms of references for both horizontal and vertical components.
5. Point cloud splitting into individual point clouds representing the homogeneous environment in order to prepare the dataset for the parametrical modeling and optimize the data management.
6. Creation of parametrical primitives in order to decompose the point cloud into each architectural element and create the solid models representing each relevant element.
7. Modeling unconventional geometries such as deformed or artistic/historical elements, which do not exist in software libraries.
8. Verification of the BIM quality and functionality (interferences, interoperability, etc.) and automated extraction of two-dimensional tables, rendering and virtual tours.

The most critical issues encountered in the methodology are twofold: firstly, the design of the survey so that it is able to provide an adequate 3D point cloud with respect to the final required LOD of the BIM; secondly, the modeling of unconventional geometries, that need to be fully read, modified and managed by any BIM software. Anyone that will deal with the BIM in the future, might choose a different software and still needs to be able to fully exploit it. This means to respect the IFC (Industry Foundation Class) common standards (buildingsmart.org/ifc).

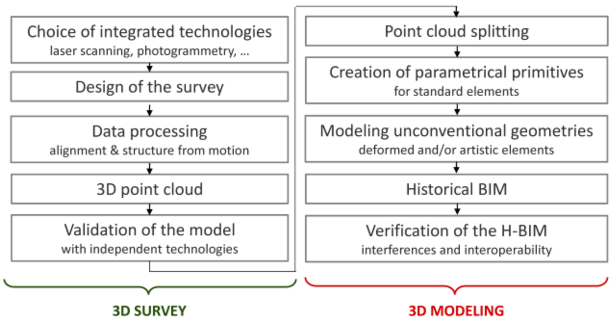

Figure 1. Workflow of the methodology highlighting the basic steps of the 3D survey and the 3D modeling, both essential for a reliable and proper final BIM.

3. THE SURVEY

3.1 The case study

The Basilica of St. Stefano in Bologna (Italy) is a complex with many juxtaposed religious buildings over the centuries. The site is also known as the “complex of seven churches” even if this number is not reflected in the structures that actually constitute it. The name, indeed, could be a symbolic reference to a number which has a strong eschatological value in the Scriptures. Currently the complex consists of (Figure 2): 1-3. Church of the Holy Crucifix, with the Crypt; 4. Church of the Holy Sepulchre; 5. Church of the Saints Vitale and Agricola; 6. Pilate’s

Courtyard; 7. Church of the Trinity or of the Martyrium; 8. Cloister; 9-10-11-12. Chapel of the Bandage and museum.

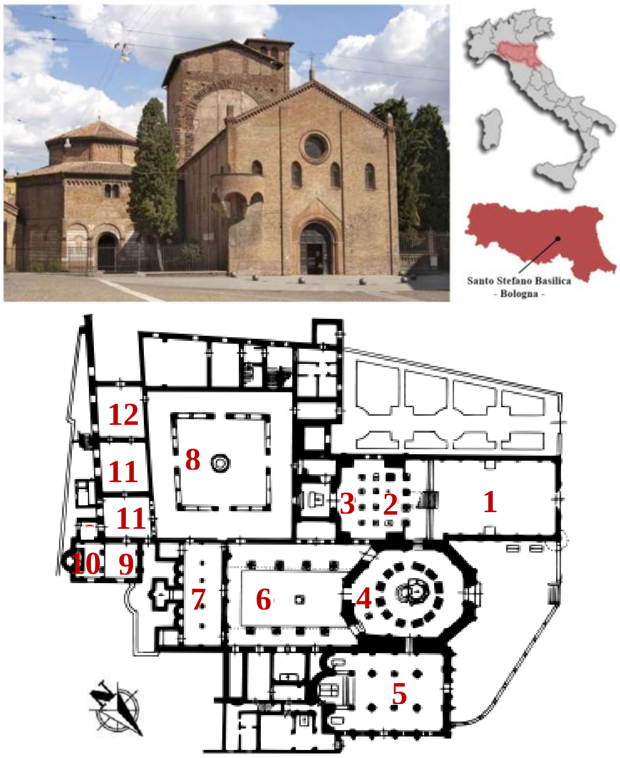

Figure 2. The Basilica of St. Stefano, Bologna (Italy). Picture of the front view from St. Stefano Square (top left); location map (top right); map of the numerous religious buildings characterizing the monument (bottom).

The origin of the complex lies in the temple dedicated to the goddess Isis (Gelichi and Curina, 1991; Ortalli, 1996; Cardini, 2015; Borghi, 2010) that was built between 80 and 100 before Christ in the place where there was a necropolis outside the roman Bononia urban area, close to the important Emilia Street (today, Strada Maggiore). When Ambrogio, bishop of Milan from 374 to 397, found the bodies of the martyrs Vitale and Agricola in 392 or 393, in a nearby Jewish cemetery (Ambrosius; Bocchi, 1996; Borghi, 2010), their remains were moved to this Christian funerary enclosure, which became a pilgrimage destination and where, probably, at the beginning of the 5th century, a chapel was built facing East on the site of the Church of the Trinity, formerly the Church of Martyrium (Donini and Belvederi, 1924; Wasserman, 1966; Nikolajevic, 1985; Benati, 1997). According to the medieval tradition of Bologna (Fanti, 1987), during the 5th century Petronio, bishop of the town, would have consecrated the existing buildings to the martyr St. Stefano and would have restructured them in imitation to the places of the Passion of Christ in Jerusalem, especially the church of the Holy Sepulchre (Fasoli, 1987; Porta, 1996; Cardini, 2015) which then would have welcomed his remains (before being transferred to the homonym church in 2000). Within the Sepulchre, he redeployed the seven marble columns belonging to the original temple of Isis and still visible today. The definition "*Sanctum Stephanum qui vocatur Sancta Hierusalem*", indeed, appears in a document of the 887 (Kehr, 1937), but the choice to reproduce the Basilica, the courtyard and the Holy Sepulchre of Jerusalem, as constructed by Constantine in the 4th century however inverting the order, could date back to San Petronio. Despite various renovations and expansions occurred over the centuries, the complex of St. Stefano as it appears at our eyes today, has kept the general structures built between the 11th and 12th centuries intact (Ousterhout, 1985).

3.2 Design and execution

The BIM approach was immediately considered the most effective strategy to deal with a so large and complicated monument as the St. Stefano Basilica. The survey was carried out in 2012 by means of a time-of-flight laser scanner, model *ScanStation C10* by *Leica Geosystems* (hds.leica-geosystems.com), with a dual-axis compensator able to guarantee the coherence between the z-axis and the vertical to the geoid. By this way, any following analyses regarding overhangs and tilting of portions of the monuments are reliable and facilitate the interpretation of final maps. Figure 3 shows some of the scanning positions, particularly those located at the ground floor, as planned and executed in order to cover the whole monument in the optimized way. The resolution was set at 5 mm in order to guarantee a full and comprehensive point cloud capable to fulfill the final requirement in terms of representation scale. The BIM as well as the 2D drawings are indeed expected to be at 1:50 scale. Table 4 gives further details about the laser scanning survey.

Figure 3. Map of the scanning positions during the survey of St. Stefano Basilica. In order to ensure greater readability, the map shows only some of the performed scanning locations and in particular those relating to the ground floor.

In order to accomplish the survey of highest parts and provide a total description of the monument, an unmanned aerial vehicle coupled with the modern photogrammetry based on *Structure from Motion* algorithms was adopted (Ullman, 1979). The platform is an esacopter, the *ESAFLY 2500* by *SAL Engineering* (www.salengineering.it) equipped with a calibrated camera, model *Canon 550D* (Table 5). The flight was planned in order to guarantee an overlap of at least 80% alongside and 60% across side. Such a design allowed to fully survey the highest part providing a 3D point cloud that is suitable, in terms of resolution and accuracy, to be integrated together with the laser scanner-based 3D point cloud of the rest of the monument.
The overall survey was designed to integrate both the laser scanning and the modern photogrammetry approaches in order

to achieve the final goal: to provide a comprehensive 3D point cloud that allows the creation of a BIM, and consequently of traditional two-dimensional technical tables, at a representation scale of 1:50.

Parameter	Value
Scanning positions	445
Mean scan resolution	5 mm
Collected points	More than 6 billions
Average scan duration	30 minutes
Working days	20
Alignment strategy	Homologous points identification + ICP algorithms
Max alignment error	5 mm

Table 4. Detailed information about the laser scanning survey as performed in the St. Stefano Basilica in 2012.

Property	Information
Dimension	100 cm (diameter) - 30 cm (height)
Weight	3.3 kg (with batteries)
Duration	12÷20 min (depending on type of batteries)
Max payload	2.5 kg (with gimbal, reflex camera and synchroniser)
Mechanics	Fully carbon with derlin inserts
Flight	Fully automated with waypoints

Table 5 Technical information about the UAV esacopter, model *Esafly 2500* by *SAL Engineering*, used at St. Stefano Basilica.

3.3 Data processing and validation

The laser scanning data processing consists in removing the parts which are not of interest, filtering the noise in the dataset and mainly aligning each scan performed from the scheduled scanning locations. The procedure lies in translating and rotating each scan to a common coordinate system (Watson, 2006) so that the final unified 3D point cloud fully describes the geometry of the monument. The alignment was carried out by means of multiple strategies such as the identification of homologous points, some retro-reflective targets that need to be recognized within multiple scans, and the surface matching based on common scanned areas. The last strategy is based on the Iterative Closest Point (ICP) algorithm (Besl and McKay, 1992; Chen and Medioni, 1992; Zhang, 1994). The alignment process provided a good final result and the maximum accepted error in the process was 5 mm (Table 4). The process was performed by the software *Cyclone* by *Leica Geosystems* (hds.leica-geosystems.com).
The UAV image processing was carried out by means of the software *Photoscan* by *Agisoft* (www.agisoft.com) and provided a UAV-based 3D point cloud which was then aligned to the laser scanner-based point cloud by means of the ICP approach with a maximum error of 2 mm (Figure 6). A comprehensive 3D point cloud of the whole Basilica of St. Stefano was obtained.
In order to provide a reliable 3D point cloud for the following BIM creation step, some verifications are required regarding the horizontal and vertical components. Multiple techniques were integrated in order to provide the cross check of results as well as the verification of the model accuracy. The validation of horizontal components was carried out by performing a high precision survey with the total station, model *TCR1201+* by *Leica Geosystems*: about 40 targets were chosen among the one installed and used for the laser scanning alignment (see top of Figure 7).

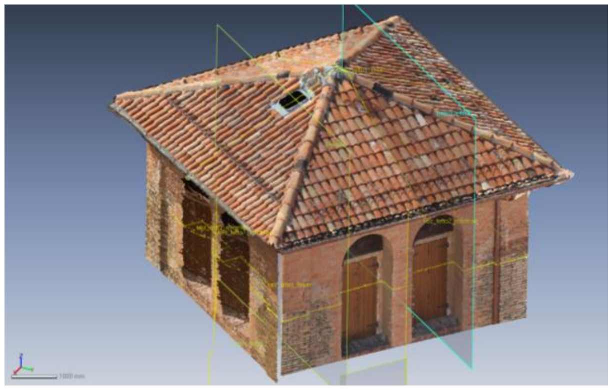

Figure 6. Image-based 3D point cloud model as obtained by means of the UAV flights: top of the tower, the highest portion of roof of St. Stefano Basilica.

The targets were measured following a network sketch with adequate redundancy. The least square network adjustment was performed by means of the software *STAR*NETPRO v. 6.0.36, Starplus Software Inc*; the final achieved accuracy was 10 mm (at 95% level of confidence). The targets that were surveyed by the total station were also identified within the laser scanning point cloud and the coordinates recorded (see bottom of Figure 7).

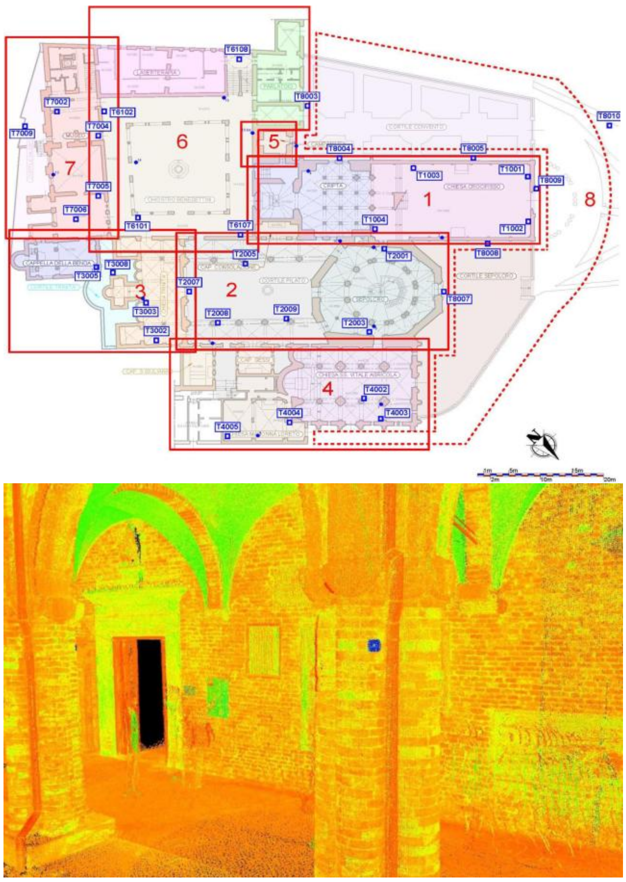

Figure 7. Validation of horizontal component: map of the selected targets that were surveyed by the total station (top); example of target as identified within the laser scanning dataset for the coordinates comparison (bottom).

Some of the targets, about 15, were used to compute rotations and translation parameters in order to make the laser scanning dataset comparable with the total station one. The remaining 25 targets were transformed into the common coordinate system and then the coordinates compared to the homologous obtained by the total station. The maximum observed difference is 10 mm with a standard deviation of 5 mm, confirming the quality and the reliability of the 3D survey horizontal components for providing an adequate final BIM at 1:50 scale.

The validation of vertical components was carried out in a similar way: a high precision leveling network consisting in 17 new benchmarks was installed within the whole monumental complex (Figure 8) and surveyed by means of a digital level, model *DNA03* by *Leica Geosystems*, and an invar staff to minimize the problem of thermal deformations, which might affect the quality of the measurements. The network was adjusted by constraining all benchmarks to a reference point that is installed in St. Stefano Square, outside the monument, and belongs to the Municipality network for monitoring the subsidence phenomenon. The data preprocessing lies in controlling the closure of leveling rings before proceeding to the network adjustment (Castagnetti et al., 2016). The survey of the 21 rings lasted two working days; the network geometry and the number of measurements are sufficiently redundant to allow a high-quality computation, thus obtaining an average accuracy of 0.4 mm (95% level of confidence) for the final elevations. The computation was performed by *STAR*NETPRO v. 6.0.36, Starplus Software Inc*.; the reference point was conventionally fixed at an elevation of 10 m. The same reference point was also recognized within the 3D point cloud and rigidly translated to the same elevation. By this way, all the benchmarks were identified and the vertical components recorded to be then compared to the leveling-based elevations. The maximum observed difference is 6 mm with a standard deviation of 2 mm, confirming the quality and the reliability of the 3D survey vertical components for providing an adequate final BIM at 1:50 scale.

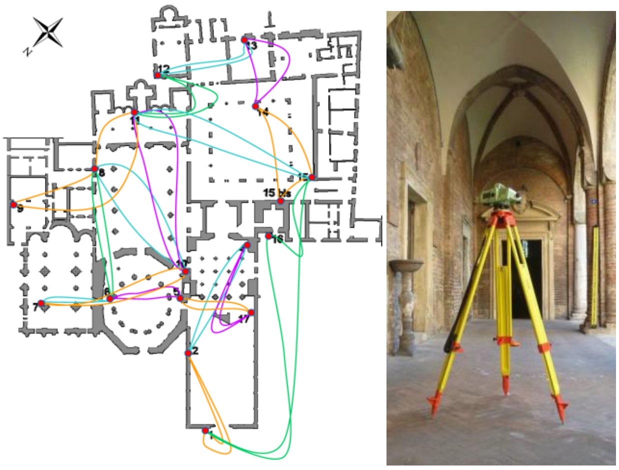

Figure 8. The leveling network consisting in 17 benchmarks (left); the digital level, *DNA03* by *Leica Geosystems*, during the leveling campaign in St. Stefano Basilica.

4. THE BIM MODELING

The obtained 3D point cloud, although accurate and complete, appears as a set of unsorted data to the eyes of an end user. The graphic representation is the crucial step in which all the collected information are interpreted in the most effective way by an experienced operator who then translates them into a set of comprehensive and consistent representations. These representations are now directly usable from the end user.

Dealing with a particularly extensive and complicated architectural complex, such as the case study, the very first step lies in disassembling the complex in homogeneous spatial environment, as shown by several colors in Figure 9. This is essential to be able to handle more manageable datasets: in agreement with that logical mindset, the total point cloud was split into individual point clouds referred to the previously identified spatial environment. Each individual point cloud was divided into portions useful to the three-dimensional reconstructions of the spaces.

Figure 9. Creating the BIM of St. Stefano Basilica: logical decomposition of the monument in several homogeneous spatial environments, each one colored by different colors. An individual point clouds is obtained for each spatial environment by the splitting the total point cloud.

The particular complexity of historical surfaces (architectural details, design variations, static deformations, irregularities and inconsistencies, instabilities, and so on) required a multidisciplinary approach to represent in the most efficient way the geometric nature of the object. Considering the general purpose of the work, the modeling process targeted a hypothetical LOD level of 200 (compared now to LOD B in the new Italian regulations, named UNI 11337) and then turned to grasp especially masonry systems (with the relative openings) and structural systems with their tracking irregularities (Barazzetti at al., 2015a). The employed modeling strategy mainly exploited the traditional approach for creating 3D solid primitives by means of NURBS (Non Uniform Rational Basis-Splines) and LOW-POLY meshes (Tang et al., 2010; Barazzetti at al., 2015b). Then, all the created primitives were translated in simple solid meshes. When dealing with surfaces that are irregular and strongly deformed, it is worth to follow the statistical approach by directly transforming the portion of point cloud into triangulated mesh before converting into solid element. Once the modeling step was completed, the solid elements were imported into the BIM environment where the morphological characteristics were added to each element; this step is useful for the 2D and 3D graphical representation (Figure 10).

The final Historical BIM was then ready to be consulted and to provide suitable representations to final fruition: extraction and query tools allows to provide the traditional two-dimensional tables (plans and sections) as well as more impressive products such as rendering (Figure 11) and virtual tours. The final H-

BIM becomes itself a delivered product thanks to the export according to the IFC, the standard and open data exchange format, capable of retaining all the main characteristics of the typological objects.

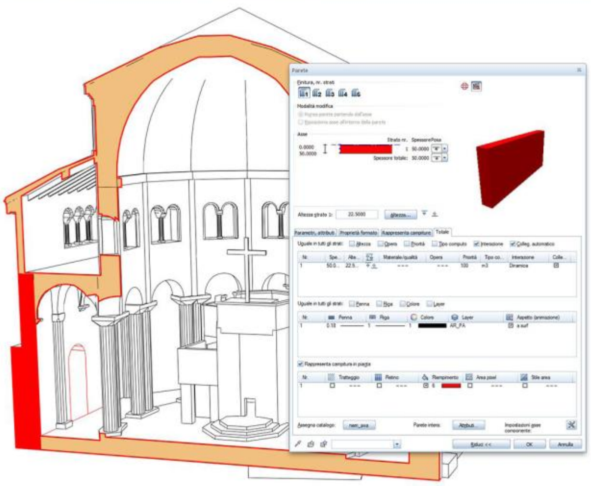

Figure 10. From the solid mesh to the BIM: example of the addition of the morphological characteristics to a modeled solid element within the Holy Sepulchre.

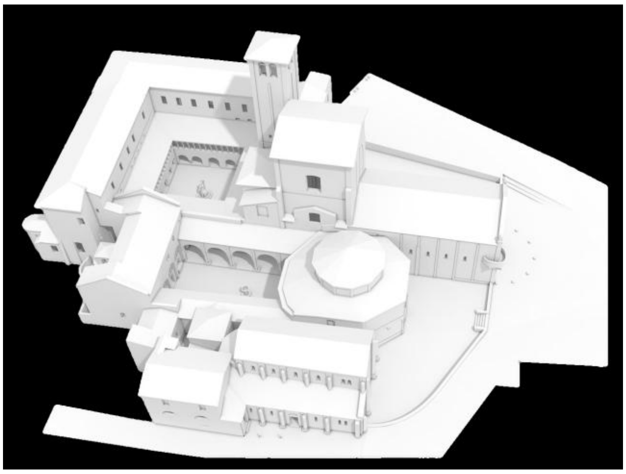

Figure 11. 3D Rendering of the full final H-BIM of St. Stefano Basilica (LOD 200).

5. CONCLUSIONS

The BIM approach is quickly gaining in popularity and promises to change the construction, engineering and architecture industries forever thanks to the suitability in managing existing buildings and the efficiency for revamping and restoration. By focusing on these markets, indeed, such a successful strategy can strongly contribute to the re-launching and the future of the entire construction sector. Despite these big potentialities, there are no regulations nor guidelines directly and comprehensively dealing with the topics of surveying methods and data processing strategies to provide a starting point for the BIM process. The success of the BIM approach in terms of productivity and dissemination among professionals also depends on the development of a definite method for data management and data treatment to be properly included into the BIM process workflow.

Thus, the paper aims at filling up the actual absence of guidelines and at delivering a comprehensive workflow from the survey to the BIM achievement, particularly for the as-built applications. The investigation of an extended and complicated case study such as St. Stefano Basilica, allowed to highlight the most crucial points in the process which are: the capability to provide a comprehensive point cloud describing the geometry of the whole building and the suitable accuracy with respect to the final BIM representation scale. For the optimization of the whole workflow, the resolution should not be unnecessarily high because the dataset becomes hardly manageable from the computational point of view nor unnecessarily low because otherwise it is not able to guarantee the required detail of representation. One more critical issue lies in the need of modeling unconventional and irregular geometries paying attention to the data interoperability.
As a conclusion, the lesson learned by the described experience links the quality of the BIM to the reliability of the surveying and modeling phases, underlying that the proper design of each step is essential to provide a helpful final 3D model with a 3D database, especially for existing building and cultural heritage.

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REFERENCES

Aish, R., 1986. Three-dimensional Input and Visualization. *Computer-Aided Architectural Design Futures, CAAD Futures Conference Proceedings*, pp. 68-84.

Ambrosius, *Exhortatio virginitatis*, PL, 16, I, coll. 336-364.

Apollonio, F.I., Gaiani, M., Zheng, S., 2012. Bim-based Modeling and Data Enrichment of Classical Architectural Buildings. *SCIentific RESearch and Information Technology*, 2(2), pp. 41-62

Autodesk Inc., 2002. Autodesk white paper: Building Information Modeling, http://www.laiserin.com/features/bim/autodesk_bim.pdf (11 Apr. 2017).

Azhar, S., 2011. Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and management in engineering*, 11(3), pp. 241-252.

Baik, A., Yaagoubi, R., Boehm, J., 2015. Integration of Jeddah Historical BIM and 3D GIS for Documentation and restoration of historical monument. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5), pp. 29.

Barazzetti, L., Banfi, F., Brumana, R., Gusmeroli, G., Oreni, D., Previtali, M., Roncoroni, F., Schiantarelli, G., 2015a. BIM from laser clouds and finite element analysis: combining structural analysis and geometric complexity. *The International Archives* *of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5), pp. 345.

Barazzetti, L., Banfi, F., Brumana, R., Previtali, M., 2015b. Creation of parametric BIM objects from point clouds using NURBS. *The Photogrammetric Record*, 30(152), pp. 339-362.

Benati, A., 1997. La chiesa bolognese nell'alto medioevo. In: Prodi, P., Paolini, L. (Editors), *Storia della chiesa di Bologna*, I, Bolis Edizioni, Bergamo-Bologna, pp. 7-96.

Besl, P.J., McKay, N.D., 1992. A method for registration of 3-D shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 14, pp. 239–256. doi:10.1109/34.121791.

BIM Forum, 2016. Level of Development (LOD) Specification, http://bimforum.org/lod/ (11 Apr. 2017).

Bocchi, F., 1996. Dalla grande crisi all'età comunale (secoli IV-XII). In: Bocchi, F. (Editor), *Atlante storico delle città italiane. Bologna*, I, Grafis Edizioni, Bologna, pp. 49-114.

Borghi, B., 2010. *In viaggio verso la Terrasanta. La basilica di Santo Stefano in Bologna*, Minerva Edizioni, Bologna.

Capra, A., Bertacchini, E., Castagnetti, C., Rivola, R., Dubbini, M., 2015. Recent approaches in geodesy and geomatics for structures monitoring. *Rendiconti Lincei*, 26(1), pp. 53-61. doi: 10.1007/s12210-015-0436-z.

Cardini, F., 2015. *Andare per Gerusalmme d'Italia*, Il Mulino, Bologna.

Castagnetti, C., Bertacchini, E., Capra, A., 2016. Monitoring leaning towers by geodetic approaches: Effects of subsidence and earthquake to the Ghirlandina Tower. *Structural Control and Health Monitoring*, 23(3), pp.580-593. doi:10.1002/stc.1799.

Castagnetti, C., Bertacchini, E., Capra, A., Dubbini, M., 2012. Terrestrial Laser Scanning for Preserving Cultural Heritage: Analysis of Geometric Anomalies for Ancient Structures. *Proc. of FIG Working Week*, Rome, Italy, pp. 1-13. ISBN 97887-90907-98-3.

Chen, Y., Medioni. G., 1992. Object modelling by registration of multiple range images. *Image and Vision Computing*, 10, pp. 145–155. doi:10.1109/ROBOT.1991.132043.

De Luca, L., Véron, P., Florenzano, M., 2006. Reverse engineering of architectural buildings based on a hybrid modeling approach. *Computers & Graphics*, 30, pp. 160-176.

Donini, L., Belvederi, G., 1924. *Gli scavi nella chiesa di Santo Stefano*, Azzoguidi, Bologna.

Eastman, C.M., Eastman, C., Teicholz, P., Sacks, R., 2011. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. John Wiley & Sons Inc., Hoboken, New Jersey.

Fanti, M., 1987. I luoghi e gli edifici della "Hierusalem" bolognese nella Vita latina di San Petronio. In: Bocchi, F. (Editor), *7 colonne e 7 chiese*, Grafis Edizioni, Bologna, pp. 125-139.

Fasoli, G., 1987. Le Sette Chiese: una vicenda ultramillenaria. In: Bocchi, F. (Editor), *7 colonne e 7 chiese*, Grafis Edizioni, Bologna, pp. 11-17.

Gaiani, M., Remondino, F., Apollonio, F.I., Ballabeni, A., 2016. An advanced pre-processing pipeline to improve automated photogrammetric reconstructions of architectural scenes. *Remote Sensing*, 8(3), pp. 178.

Garagnani, S., 2013. Building Information Modeling and real world knowledge: A methodological approach to accurate semantic documentation for the built environment. *Digital Heritage International Congress (DigitalHeritage)*, 1, pp. 489-496, IEEE.

Garagnani, S., 2015. Semantic representation of accurate surveys for the cultural heritage: BIM applied to the existing domain. *Emerging Digital Tools for Architectural Surveying, Modeling, and Representation*, pp. 292-310.

Gelichi, S., Curina, R., 1991. Vecchi e nuovi scavi nell'area del complesso stefaniano. In: Scannavini, R. (Editor), *La piazza S. Stefano, da trebbo medievale a piazza prospettica rinascimentale*, Grafis Edizioni, Bologna, pp. 97-122.

Kehr, P., 1937. *Dipl. regum et imperatorum Germaniae ex stirpe Karolinorum, II, 2*, Weidmann, Berlin, n. 171, pp. 272-273.

Kim, H., Anderson, K., Lee, S., Hildreth, J., 2013. Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. *Automation in Construction*, 35, pp. 285-295.

McGraw Hill Construction, 2014. The Business Value of BIM for Construction in Major Global Markets: how contractors around the world are driving innovation with building information modeling. Smart market report, http://redstack.com.au/lib/pdf/Mcgraw_Hill_BIM_Report.pdf (11 Apr. 2017).

Menna, F., Nocerino, E., Remondino, F., Dellepiane, M., Callieri, M., Scopigno, R., 2016. 3D Digitization of an heritage masterpiece – A critical analysis on quality assessment. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B5, pp. 675-683.

Mitchell, W.J., McCullough, M., 1995. *Digital design media*. John Wiley & Sons.

Murphy, M., McGovern, E., Pavia, S., 2013. Historic Building Information Modelling – Adding intelligence to laser and image based surveys of European classical architecture. *ISPRS Journal of Photogrammetry and Remote Sensing*, 76, pp. 89-102.

Nikolajevic, I., 1985. Area cimiteriale di Santo Stefano in Bologna. In: Fasoli, G. (Editor), *Stefaniana. Contributi per la storia del complesso di S.Stefano in Bologna*, Deputazione di Storia Patria, Bologna, pp. 51-66.

Ortalli, J., 1996. Bononia Romana. In: Bocchi F. (Editor), *Atlante storico delle città italiane. Bologna*, I, Grafis Edizioni, Bologna, pp. 29-45.

Ousterhout, R.G., 1985. Santo Stefano e Gerusalemme. In: Fasoli, G. (Editor), *Stefaniana. Contributi per la storia del* *complesso di S.Stefano in Bologna*, Deputazione di Storia Patria, Bologna, pp. 131-158.

Porta, P., 1996. Architetture di Bologna prima del Mille. In: Bocchi, F. (Editor), *Atlante storico delle città italiane. Bologna*, I, Grafis Edizioni, Bologna, pp. 65-67.

RIBA Enterprises Ltd., 2016. NBS International BIM Report 2016, https://www.thenbs.com/knowledge/national-bim-report-2016 (11 Apr. 2017).

Santagati, C., Turco, M.L., 2017. From structure from motion to historical building information modeling: populating a semantic-aware library of architectural elements. *Journal of Electronic Imaging*, 26(1).

Saygi, G., Agugiaro, G., Hamamcioglu-Turan, M., Remondino, F., 2013. Evaluation of GIS and BIM roles for the information management of historical buildings. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, II-5/W1, pp. 283-288.

Smith, D.K., Tardif, M., 2009. *Building information modeling: a strategic implementation guide for architects, engineers, constructors, and real estate asset managers*. John Wiley & Sons Inc., Hoboken, New Jersey.

Tang, P., Huber, D., Akinci, B., Lipman, R., Lytle, A., 2010. Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques. *Automation in construction*, 19(7), pp. 829-843.

Ullman, S., 1979. The interpretation of structure from motion. *Proceedings of the Royal Society of London B: Biological Sciences*, 203(1153), pp. 405-426.

Van Nederveen, G.A., Tolman, F.P., 1992. Modelling multiple views on buildings. *Automation in Construction*, 1(3), pp. 215-224.

Wasserman, J., 1966. *Ottaviano Mascherino and his Drawings in the Accademia Nazionale di San Luca*, Accademia Nazionale di San Luca, Roma.

Watson, G.A., 2006. Computing Helmert transformations. *Journal of Computational and Applied Mathematics*, 197, pp. 387–394. doi:10.1016/j.cam.2005.06.047.

Zhang, Z., 1994. Iterative point matching for registration of free-form curves and surfaces. *International Journal of Computer Vision*, 13, pp. 119–152. doi:10.1007/BF01427149.

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DUBBINI M.: 3D integrated survey coordination, design and execution.

RICCI P.C.: 3D modeling and BIM creation.

RIVOLA R.: 3D survey execution and data processing.

GIANNINI M.: historical documentation on the case study (section 3.1)

CAPRA A.: project fund raising.