A HYBRID MODEL FOR THE REVERSE ENGINEERING OF THE MILAN CATHEDRAL. CHALLENGES AND LESSON LEARNT

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Abstract:

Cultural Heritage (CH) 3D digitisation is getting increasing attention and importance. Advanced survey techniques provide as output a 3D point cloud, a complete and accurate description even of the most complex architectural geometries with *a priori* established accuracy. These 3D point models are generally used as the base for the realisation of 2D technical drawings and 3D advanced representations. During the last 12 years, the 3DSurveyGroup (3DSG, Politecnico di Milano) conduced an omni-comprehensive, multi-technique survey, obtaining the complete point cloud of Milan Cathedral, from which were produced the 2D technical drawings and the 3D model of the Main Spire used by the Veneranda Fabbrica del Duomo di Milano (VFD) to plan its periodic maintenance and inspection activities on the Cathedral. Using the survey product directly to plan VFD activities would help to skip a long-lasting, uneconomical and manual process of 2D and 3D technical elaboration extraction. In order to do so, the unstructured point cloud data must be enriched with semantics, providing a hierarchical structure that can communicate with a powerful, flexible information system able to effectively manage both point clouds and 3D geometries as hybrid models. For this purpose, the point cloud was segmented using a machine-learning algorithm with a multi-level multi-resolution (MLMR) approach in order to obtain a manageable, reliable and repeatable dataset. This reverse engineering process allowed to identify directly on the point cloud the main architectonic elements that are then re-organised in a logical structure inserted inside the informative system built inside the 3DExperience environment, developed by Dassault Systémes.

Keywords: cultural heritage, classification, reverse engineering, point cloud, machine learning, BIM

1. Introduction

The Veneranda Fabbrica del Duomo di Milano (VFD, 2021) is the organisation responsible of the construction, maintenance and development of Milan Cathedral since the very beginning of its history, in 1387; through more than six centuries the VFD operated using the techniques of the time and collecting records and documents of all the operations.

Nowadays the archives host a prosperous deposit of information, derived from the VFD activities, that should be made entirely consultable and kept up to date with new entries from the present and future operations.

There is a significant and evident awareness that the only feasible way to obtain an efficient and organised system for the study and fruition of the archived data can only rely on the digital form. However, it is also clear that lots of questions should find answer before taking the first step in this direction.

The rapid acceleration given to our society and activities by the digitisation process requires to have at disposal a large amount of information available in real-time, organized in such a way that it is possible to manage them in an efficient and intuitive way. The interaction between end-users and data repositories design should be inspired by immediate usability and a reduced learning phase.

Professionals working in the Cultural Heritage field (as conservators, archivists, restorers, designers, project managers...) that take care of grand historical architectures are today thoroughly evaluating the advantages of a full digital transition of their internal processes and archives, which brings to the crucial question of how to proceed in this transition and how to face the proficient management of huge data set.

The VFD is nowadays confronting with this topic and questioning itself about the most suitable way to proceed, exploring some solutions together with Politecnico di Milano.

Should the robust logical structures that have been adopted by the curators of the Historical Archives be reproduced inside an articulated database? Which

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digitisation strategy for the existing architecture can be pursued in order to construct a reliable three-dimensional basis, a digital twin of the Cathedral, in order to extract useful information and provide a support for knowledge and dissemination? How to secure a long-term investment that should be profitable for many years, considering the speed at which technological tools evolve and become obsolete nowadays? It is possible to adopt a lean approach that can focus on specific parts according to the present needs of the VFD? Which strategy can provide significative results in a short time, relying on the already present data and carrying on the already open projects?

The activities that VFD and Politecnico di Milano conducted together over the last ten years (Achille et al., 2020) represented a significant experience on the topic of digitisation of Cultural Heritage and an occasion to encounter both well-known and unexpected problems in the management and proficient use of such extended dataset. The complete point cloud of the Cathedral, obtained as final product of the survey activities and data elaboration, proved itself as a promising candidate to be the three-dimensional basis for the realisation of the digital twin of the monument, providing an adequate answer to some of the questions that, as previously described, VFD was posing to itself.

The awareness of the possibilities offered by the point cloud of the Cathedral grew as the survey went on: it started as a data-gathering campaign, experiencing considerable difficulties due to the extension of the monument that needed a thorough design of the operations, for the realisation of 2D updated technical drawings, according to the needs of the restoration yard at that time. The step that followed was to imagine what else could be derived from such complete data, and several 3D models were realised.

Nowadays, the main topic regards what the whole point cloud can be transformed into without losing its metrological accuracy, and how to integrate it with all the previously produced material and data.

Such a heterogeneous repository of knowledge could be effectively organised and used inside a Heritage Building Information Model (HBIM) environment, but the overall complexity of the monument and the need for metrologically accurate data inevitably pose questions about the most appropriate and efficient way to pursue this goal. The experience gathered in the past years showed that "modelling-time" and "yard-time" usually do not correspond, as the strict schedule of the restoration yard could not wait for models to be accomplished in order to extract the measurements and data needed for the operations: a compromise between speeded up digitisation and accuracy of the shape should be found. In this sense, the point cloud can be a resource to be directly used, if enriched with semantics, with the recognition of the specific architectural objects and structured inside an informative system with all the related and useful data.

The very recent and experimental applications that the research group is developing on the Cathedral point cloud showed encouraging results in terms of categorisation and recognition of the constitutive elements of the architecture, using automatic machine-learning algorithms.

The considered solution allows building a semantic model of the architecture avoiding the time-consuming traditional modelling activity (direct or parametric-based), which can bring to uncertain results depending on the ability of the operator. Moreover, starting from the segmented point cloud, also the real-based modelling operation can be accelerated and benefit of a direct reference for metrological comparison of the shapes.

The model obtained could act as a support for the archive of the remarkable amount of data gathered about the Cathedral during the centuries, linking the information to the architectural elements it refers to. The user experience can indeed benefit from a visual navigation tool founded on the real shape of the architecture for the retrieving of the restoration data, while the pre-existent structure of the archive should be preserved and carefully implemented in the new system.

The archiving is linked to the physical evidence of the architectures, consequentially very intuitive and user-friendly while ensuring respect for the structure and complexity of any archival system that is to be made available and accessible through the model itself and the appropriate relational links. Moreover, as required or necessary, the classified point cloud can facilitate and speed up also the modelling process in the most classic sense.

This paper, presenting the current research activities and their up-to-date results, aims to provide possible answers, encouraging solutions and feasible strategies to some of the question here exposed.

2. The Reverse Engineering of Cultural Heritage

For Reverse Engineering of Cultural Heritage is here intended a digitisation strategy for the historical architecture, which is based on three-dimensional survey and semantics, a complete virtual reconstruction of an existing object (Fassi & Parri, 2012). This implies not only the accurate digital reconstruction of the shape of the architectural elements (De Luca, Veron, & Florenzano, 2006; Dore & Murphy, 2013) but also the deep understanding of the architecture-system and the identification of its components and their mutual interrelationships in order to create a representation of the system itself (Chikofsky & Cross, 1990; Rekoff, 1985).

It produces a 3D informative model to extract knowledge from the Monument, as a support for the maintenance activities and, also, as a repository of historical and geometrical data. The digitisation is conducted following a metrological approach: it starts with the complete 3D survey of the architecture with established accuracy and precision, which represents the best, basic geometrical knowledge of architecture in the form of an undifferentiated point cloud.

With "semantics" is here intended the act of giving a structure to the elements of the model, namely identifying them as separated objects through a label (Grilli, Farella, Torresani & Remondino, 2019) according to their architectural features and role. This structure organises the whole model and allows to navigate in it.

It is essential to define the minimum intervention object of the structure according to the maintenance needs and in

general to the use of the model. Higher levels of the structure are then defined as macro-aggregation of "unbreakable elements" according to the chosen criteria.

3. A new approach to a metrological model for Duomo maintenance

The aim of this work is to conduct a preliminary test on the possibility of using the digital tools belonging to the manufacturing industry field for the digitisation of Cultural Heritage and as a support to the maintenance practices, taking a further step in the informative modelling process for Milan Cathedral, started in 2011 with the realisation of the Main Spire model (Fassi, Achille, & Fregonese, 2011).

3.1. General system requirements

The followed metrological approach guarantees that the model is precise and accurate, and that should be suitable for a 1:50 and 1:20 representation scale, with a 2 cm and 1 cm tolerance. According to this value all elements, including the decorative apparatus (when needed), are modelled.

The final element of the semantic structure has to be the marble block, which should be automatically computed the volume and the area of the external surface. This means that for marble bocks the modelling phase cannot be avoided, and inside the established internal model tolerances, the CAD objects representing the marble blocks must be closed (watertight) in order to be recognised as a solid. To achieve the required precision, modelling activities should be based on point cloud objects, that have to be importable and manageable inside the software. In particular, it should be possible to visualise the point clouds correctly, to cut cross-sections in order to obtain modelling profiles and perform deviation analysis to evaluate in quantitative terms if the modelled geometry is adequate for the established precision.

During the past years, several feasibility tests have been conducted in order to find which software (or software combination) could provide useful modelling tools able to reach the required metrological accuracy and how to manage the informative part related to the 3D geometries (Lo Furno, Pietrucci, Tommasi, & Mandelli, 2016; Tommasi & Achille, 2017).

The leading BIM software are generally designed to cover the needs of the new constructions, in which architectural elements and procedures are usually standardised: consequently, the modelling tools embedded in BIM software can be unsuitable to the elaborated and complex geometries that are typical in the Cultural Heritage field. On the other hand, 3D modelling software as Rhinoceros offer tools able to reach considerable precision and complexity in modelling, but they may lack the point cloud support and could need external resources in order to manage the informative part and attached documents (Tommasi & Achille, 2017). As an example of how the Cultural Heritage field has specific needs in terms of flexibility, both in modelling and data management, is here mentioned the case of Parma Cathedral, which used Autodesk Revit (Autodesk, 2020) as a general model manager, but integrated with an external software for the management of the data repository and the user interface for restorers (Bruno & Roncella, 2018; Bruno & Roncella, 2019).

In terms of data management, the objects should be enriched with the information related to their condition and the maintenance operations, also with the possibility to attach external data; a more advanced requirement would be the ability to manage the informative part directly on the point cloud, which will become in this way an object of the model and not only a geometrical reference.

The previously and future-realised models should be importable and managed inside the software in order to ensure the continuity of data and work.

The needs and requirements here expressed were addressed through a proficient answer with the BIM3DSG system (Fassi, Achille, Mandelli, Rechichi, & Parri, 2015), a device to manage and store the complex and huge amount of data built through the years, to enrich it with information though specifically created attributes and to visualise geometries on the internet, with no application needed but a web-browser (Rechichi, Mandelli, Achille, & Fassi, 2016). The system is based on open-source libraries; it manages both NURBS and mesh objects, and automatically adapts visualisation performances according to the device. It was designed to be fully adaptable: among the others, it is used in Saint Mark Basilica in Venice (Fregonese, Adami, 2020) in Sacri Monti of Piedmont and Lombardy (Tommasi, Fiorillo, Jiménez Fernández-Palacios, & Achille, 2019) and even for sculpture, as the Michelangelo's Pietà Rondanini (Mandelli, Achille, Tommasi, & Fassi, 2017) case. The system is structured in two different macro-entities: Back and Front Office (Fassi & Parri, 2012): Back Office represents the authoring part: it comprehends the modelling part of geometry performed inside Rhinoceros (2021), which is linked to the online database through a plugin, and has privileges of reading and writing for all the data; the Front Office is the web-based interactive part for users, which can be passive (only consultation of data) or active, being allowed to modify attributes and non-geometrical data, like photographs. The BIM3DSG system is optimised for touch screen and mobile devices in order to be used directly in the restoration yard as a tool for locating the blocks and update information on the field: it is at the same time an operational tool and a logbook of the Monument's management through time, and its latest development, Chimera, provides support and integrates GIS data inside the HBIM environment (Bruno et al., 2020; Rechichi, 2020) (Fig. 1).

Considered all the gained experience about the digitisation of Milan Cathedral and the needs and the *modus operandi* of its restoration yard as previously described, the intention nowadays is to search for an integrated system, as a software platform, in which perform all the operations that may derive from the processed and segmented point cloud. The idea is to find a powerful digital tool suitable to build the digital twin of the Cathedral and daily support of the activities of the Veneranda Fabbrica all inside the same common environment, without data duplication and effort and energy dissipation.

The quest for this kind of digital tool was directed to the mechanical and manufacturing sector, in which the operational needs can be comparable: metric modelling up to precise tolerances and consequently the need of embedded tools to perform geometrical verifications, the management of complex and articulated CAD models, the guarantee of rigorous topology for the 3D modelled

elements and the integration and management of different information systems at different level of usability.
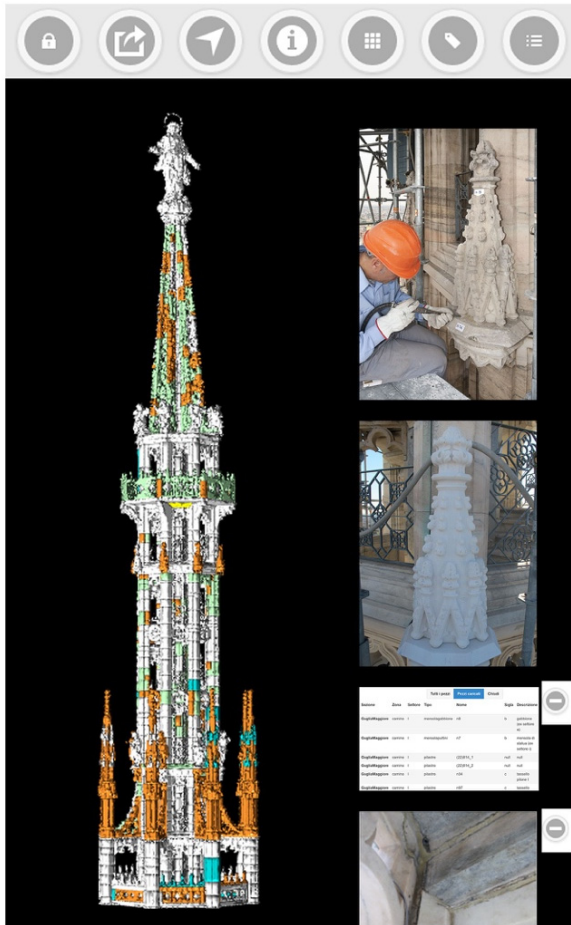

Figure 1: The BIM3DSG web system, showing the entire model of the Main Spire, coloured according to the maintenance status and the attached information of a decorative element (Achille et al., 2020).

3.2.   The 3DExperience platform

The tested solution is the 3DExperience platform developed by Dassault Systèmes (Dassault Systèmes, 2020). It is an ensemble of different software engines for 3D modelling, computational simulation, product management and manufacturing, among the others, able to work in symbiosis sharing the same data, which are stored in a common online database.

The fields of application span from the manufacturing sector to the mining and biomedical ones: wherever it is necessary to model, manage complex geometries and run simulations; the main application is as Product Lifecycle Management (PLM) software in the manufacturing context, as the platform is able to manage all the phases of the product lifecycle, from the first mock-ups and design sketches to the assembly line and even the dismantling at the end of the lifecycle of the product. Each software engine has several *development environments* (also called "apps") designed to accomplish a task, which can be very general, like solid or surface modelling, or very specific, like to design the reinforcement of carbon fibre panels or to optimise the product packaging.

The 3DExperience is web-based and accessible through a common web browser; the primary interface acts as a launchpad and consents to run the needed application and accomplish some tasks with the dashboard system, a customisable user interface based on the composition of "app" windows on the web page.

The cloud-based system ensures that, virtually, the services and the data are synchronised and available from everywhere and from every device. Users have an assigned role that determines their access privileges and their ability to modify or create new objects or contents, keeping every user inside its pre-established competence field, following and expanding the already consolidated logic of Front and Back Office on which the BIM3DSG was based and developed.

The 3DExperience is an integrated system in which all the operations are performed in the same environment and where the interoperability problems among different software are virtually solved, gathering together inside common platform features and roles that are usually scattered. Every operation will be conducted inside the 3DExperience, from modelling to dissemination and visualisation.

A non-trivial aspect to be considered is the one of the long-term support of the software and general reliability matter: a solution developed for the manufacturing industry and adopted mainly in the business, should guarantee stability, availability and support for all the loaded data for a long time, roughly estimated in 25 years: it is compatible with the typical lifecycle of some industrial projects, as in the aerospace field, and consequently is the usually guaranteed lifespan of backward compatibility of the dedicated software tools.

4.   The structure of the model

4.1.   A multi-source, multi-scale model

The realised model is constituted by the segmented point cloud, by the consolidated data deriving from previous modelling experiences inside the Rhinoceros software and by new models, fully realised inside CATIA. The imported data were originally made for the 1:20 scale and present the block subdivision; in this category are included all the Main Spire, the dome cladding and the dome itself, with the remarkable exception of the Madonnina statue in the top of the Main Spire, in 1:5 scale. The new data were realised in 1:50 scale and did not present the block subdivision, to be accomplished in a second phase; was modelled the interior part of the cross, namely the four pillars and the drum, on which the dome rises (Fig. 2).

The breakdown structure of the informative model is the principle upon which all the data is organised. It represents the logical but also spatial relations between the different elements. Throughout this structure, it is possible to visually navigate the model and have access to all the information stored in the database.

The adopted structure was defined starting from the one that was established developing the Main Spire project (Fassi, Achille, Gaudio, & Fregonese, 2012; Fassi, Achille, Mandelli, Rechichi & Parri, 2015) and that is currently used for its on-going restoration. Some modifications and few changes were made to cover all the

possible "object" contained in the Cathedral. Nowadays, on the same idea and principle is going to be defined as the spatial-reference interface for the digitised historical archive of the Veneranda Fabbrica.
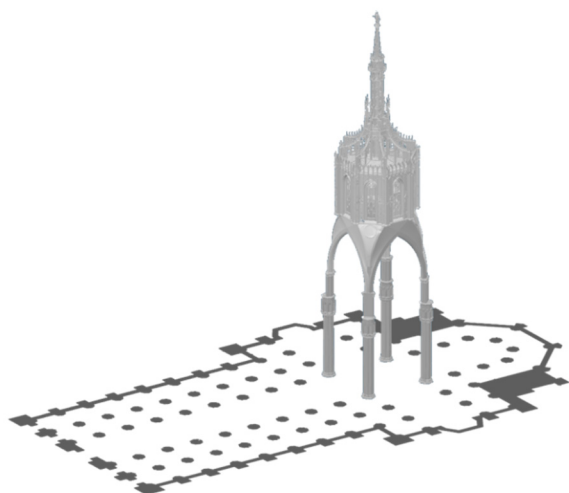

Figure 2: The position of the model inside the Cathedral, at the intersection between the main nave and the transept.

The result is an implemented breakdown structure centred on the marble block, the final element and the focus of the restoration activities, that provides five overall levels related with a logical, progressive architectural subdivision, suitable also for the yard operations, defined as follows (Figs. 3 and 4):

1) *Zone*: a portion of the Monument presenting similar intervention practices.
2) *Area*: position inside the zone according to architectural features.
3) *Sector*: specific location inside the area, as a bay for the nave.
4) *Architectural element*: a recognisable object with specific architectural function and features.
5) *Block*: final element with no possible further subdivision.

4.2. Level of Development of the model

Building Information Modelling (BIM) is nowadays a well-known and established method in the field of Architecture and Building Construction. The sector of the Cultural Heritage can indeed benefit from the tools and methods of the BIM initially developed for the new architectures. However, particular care should be used in the direct translation and application of some concepts and methodologies in the CH field, as "this might not be the most appropriate way of approaching HBIM for existing buildings" (Edwards, 2017).

This is the case of the LOD concept (here to be intended as "Level of Development") (American Institute Architects, 2008; UNI, 2017) that defines the reached level of informative evolution of a digital object (Pavan, Mirarchi, & Giani, 2017). Being developed for the field of contemporary architecture, it takes into account the informative requirements (which information should be integrated into the model) and the normal development (that follows a pre-established pipeline among all the

actors of the process) of the information modelling for the new construction (Pavan, Mirarchi, & Giani, 2017). In this work, it has been decided to take the central concept of LOD and to apply it in the specific context of the model for Milan Cathedral restoration.
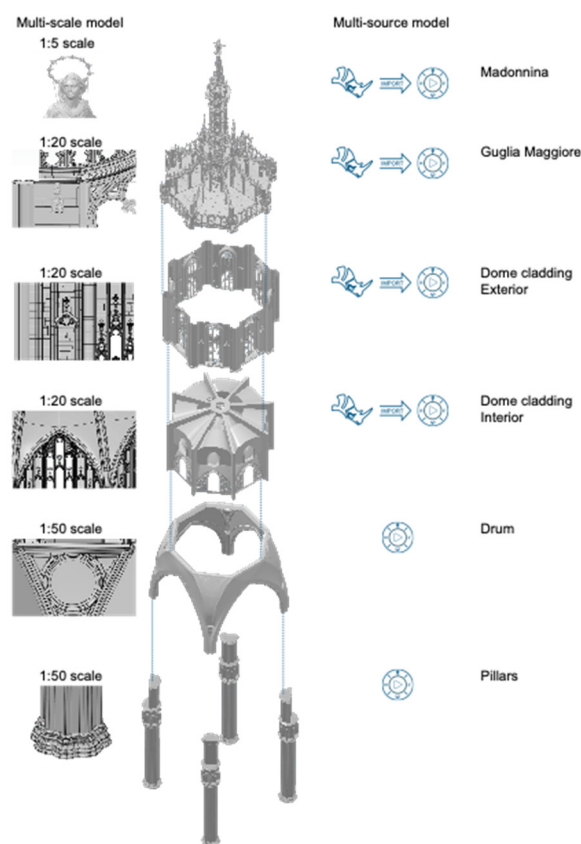

Figure 3: A schematic representation of the model with its scale and source of the objects.

As previously stated, the realised model comprehends objects at different representation scale and different resolution in terms of breakdown structure: in fact, the imported elements present the subdivision in blocks, while the new modelled ones, at 1:50 scale, do not present further subdivision than the architectural element, the fourth level in the structure. Since all the modelling of Milan Cathedral elements has always been performed on a real-based approach, they are modelled at the maximum possible accuracy offered by the point cloud, which is the product of a survey designed for that scale and to produce digital representation at the established accuracy. Any increment in the geometric level of detail is possible if a new survey is carried out at a suitable geometric accuracy. Objects are modelled "in place" at the level of the architectural element (the same in which the point cloud was segmented) and then, when needed by the restoration activities, are subdivided through a splitting operation into their constitutive blocks in order to reach the higher informative level of detail in the established structure. With this operation, the reverse engineering of the part of the Cathedral should be considered complete as the final, constitutive element of its architectural system has been reached and defined. Since the splitting operation is carried out manually and it ends to be a very time and resource-consuming, it is realised when needed by the planned activities of the restoration yard.
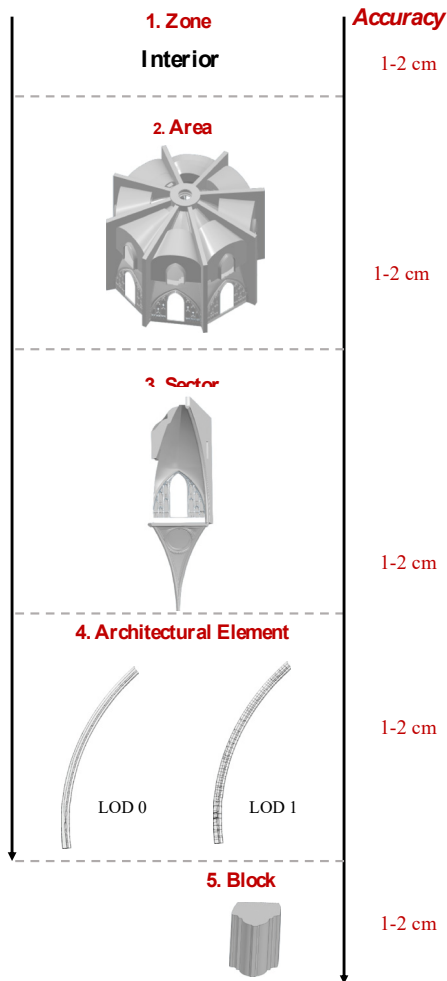
1. Zone

Interior — 1-2 cm

2. Area — 1-2 cm

3. Sector — 1-2 cm

4. Architectural Element — 1-2 cm

LOD 0   LOD 1

5. Block — 1-2 cm

Accuracy

Figure 4: A schematic representation of the logic of the breakdown structure.

In order to take into account, this progressive and localised development of the informative content of the model as the maintenance of the Cathedral proceeds, namely if the block subdivision is available for a determined architectural object, the concept of Level of Development (LOD) has been adopted: objects at LOD0 level are modelled as architectural elements and do not present further subdivision, while objects at LOD1 had been modelled as architectural elements but after were subdivided into the constitutive marble blocks. Between the two LODs there is no difference in terms of geometrical accuracy since all the model has been realised in order to comply with the representation scale, and consequently the metrological accuracy, of the reference point cloud.

5. The Digitised Cathedral

5.1. Preliminary operation: Point Cloud segmentation

The point cloud data on which the operator bases his modelling actions must be set up for the task. The raw data coming from the survey is a set of x, y, z points together with radiometric or colour information (depending on the instrument used for the acquisition).

These data are rich in metric content and describe completely the 3D geometry of the object that is surveyed but lack semantics and hierarchy among parts.

Computational requirements and the complexity inherent in such an extended dataset, like that of Milan Cathedral, make the semantic structuring of the point cloud a fundamental step preceding the modelling phase itself. Up until now, this process has been done mainly manually, with an expert operator visually interpreting and segmenting the dataset. Recent advancements in the Artificial Intelligence (AI) field made possible to develop semi-automatic Deep Learning (DL) and Machine Learning (ML) procedure that speed up the process which, otherwise, would have been as time-consuming as the modelling phase itself.

Due to the difficulties of finding a wide, enough labelled dataset to train a Neural Network for a DL approach and to ML better performance (Matrone et al., 2020), a supervised ML approach based on Grilli, Farella, Torresani & Remondino (2019) has been used to classify Milan Cathedral dataset. The authors train a Random Forest (RF) classifier manually annotating a small portion of the dataset together with geometric features designed for the architecture (Grilli, Farella, Torresani & Remondino, 2019). The size of Milan Cathedral point cloud makes it difficult to perform classification on the whole dataset. Its requirements in computational capacity make it a real challenge to manage the whole set of points. Furthermore, the necessity to distinguish among such a high number of semantic classes introduce a high degree of uncertainty leading to classification errors.

In Teruggi, Grilli, Russo, Fassi, & Remondino (2020) the method has been improved using a Multi-level Multi-resolution approach. The classification process is divided into different stages (Fig. 5).

At first, the full resolution dataset is subsampled, and the architectural macro-elements are classified by training a specific RF classifier on a 5 cm resolution point cloud. The result is interpolated on a higher resolution version of the point cloud (2 cm) so that each macro element can be further subdivided. The process is iterated until each element of the architecture is classified with increasing detail directly related to point cloud resolution and until the initial resolution is reached (5 mm).

Each step requires a new RF to be trained on its relative manually annotated portion (Fig. 6), but the small amount of required labelled data and the speed of the training and classification process make the methodology a success. Performance have been assessed with standard ML metrics (Precision, Recall and F1 score) and results are satisfactory at each classification level (Level 1: 94.7%, 95%, 93%; Level 2: 99%, 98%,99.3%; Level 3: 92%, 88.5%, 91.8% respectively) (Teruggi, Grilli, Russo, Fassi & Remondino, 2020).

Figure 7 shows Milan Cathedral 5 cm resolution point cloud classified at level 1 in its constituting macro-elements.

At the end of the elaboration, the whole point cloud is entirely composed of the sub-recognised point cloud portion that semantically describes the Duomo shape. From macro to micro-scale every element is correctly recognised and classified, like a 3D puzzle, it is possible to "disassemble" and "re-assemble" Duomo. The visual

recognition of the elements makes it easier to consult the point cloud and solves the problems of ambiguity that can be created in reading the unstructured cloud. Also, for people that have not familiarity whit this type of data is easy to consult it, they take advantage from the coloured view of the architectural object and related vocabulary (altar, floor, pillar, vault, roof).
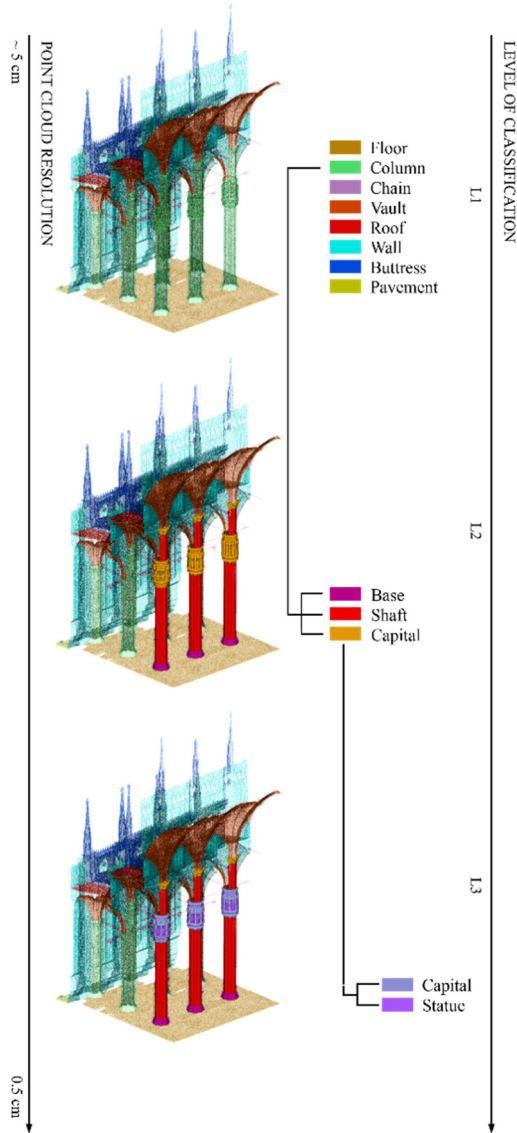

Figure 5: MLMR classification results and semantic classes. The subdivision starts from architectural macro-elements, proceed to architectural element, and reach full resolution point cloud (5 mm) for object subdivision (statues, decorations). Point cloud resolution changes according to the dimensions of elements to be recognised.

The first immediate use of this data regards the possibility to take dimensional information. Using simple tools (ruler) the user, having selected and visualised the element, is able to measure it. The second way regards the possibility to use it as a starting point to create a solid model. When it is necessary, the structured point cloud can be uploaded in different modelling software as a "base" to build the 3D shape. The entire step of point cloud contour is outdone, the modeller starts directly from the single set (single selected point cloud object). This means much time saved

and avoiding subjective interpretation of the point cloud data. This second application was tested using the sophisticated modelling tools provided by the 3DExperience platform.
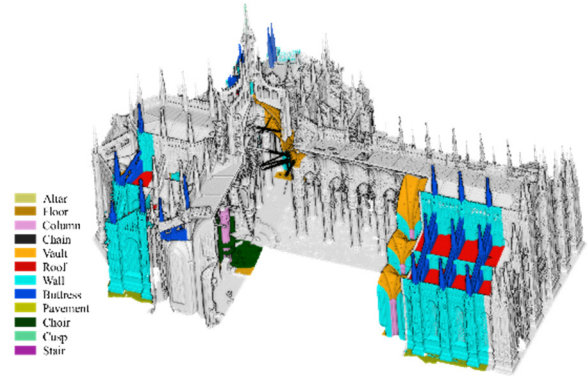

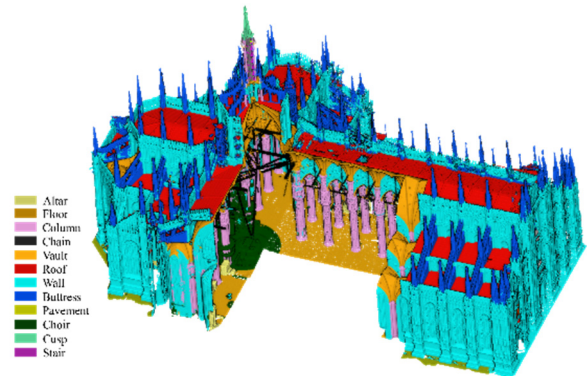**Figure 6**: Manually annotated training set for classification level.

Figure 7: Architectonic macro-elements classified at level 1 on a 5 cm resolution point cloud.

5.2.   The adopted modelling pipeline

The chosen approach was to model "in-place" starting from the already segmented point cloud, extracting the most significative cross-sections and profiles to be used as generative geometries for the modelling algorithms of the software.

The modelling engine of the 3DExperience platform is called CATIA (Computer-Aided Three-Dimensional Interactive Application) and is composed of different *development environments*, according to the task to be accomplished and the type of geometries to be modelled. The first step was to import the point cloud, appropriately segmented and filtered in dedicated software, usually Cloud Compare (CloudCompare, 2020), inside the Digitized Shape environment, that allows the user to import and process non-NURBS geometrical data, like point clouds and meshes and perform the preliminary operations of modelling. Inside this module, it is possible to manually select and extract cross-sections and profiles as subgroups of the complete point cloud, to be used in the subsequent modelling phase. These profiles are then drawn inside the dedicated environment to 2D restitution, called Sketcher, able to create bi-dimensional drawing entities on a reference plane previously established, which can be integrated with 3D splines that connect particular points, acting as guides for the modelling algorithms that will be used in the following phase. The

result of these preliminary operations is a wireframe model (Fig. 8) built by the representative profiles, cross-sections, guides and reference planes. It has to be noticed that the quality of the final model relies mainly on the ability of the operator during this phase, which is also the most time consuming, having to arbitrary decide how many and which profiles are the best solution in order to describe the considered geometry, also taking into account the available time and resources for this operation.
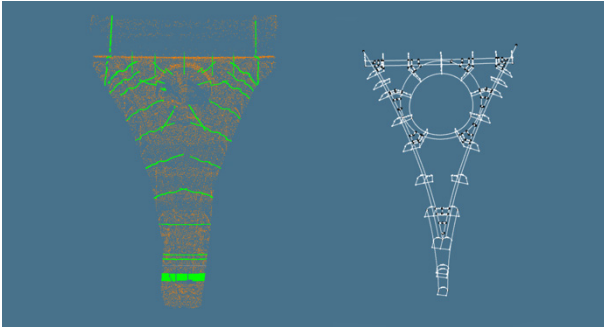

Figure 8: The extracted sections and profiles (left) and the obtained wireframe model of a pendentive (right).

The proper modelling phase, intended as the production of surface and solid 3D geometry, was conducted inside the "Part Design" and the "Generative Shape Design" environments. It can be considered partially automatised since a suitable choice of guides and profiles speed up considerably the geometry production.

CATIA provides several powerful tools based on "multi-section" input: they can build surfaces or solids interpolating between the provided sections and guides, performing in the background several single modelling operations as extrusions and sweeps based on the input geometry.

The skills and experience of the operator in this phase are expressed by its ability to split the modelling task into sub-tasks and, if needed, modify the input profiles inside the tolerances in order to help the modelling algorithms in the processing phase. Again, it has to be noticed that the final result (Fig. 9) depends on the ability of the operator to act as a mediator between the needed accuracy of the model, the possibilities of the software to build the desired geometries and the available resources, especially time.

The final step in this pipeline is the most critical in terms of reality-based modelling at an established representation scale: in order to verify that the finalised model was built inside the dimensional tolerances from the point cloud, a deviation analysis has to be performed. It gives a visual and quantitative idea of how much, and in which parts, the model respects the input geometry according to the tolerances chosen with the representation scale, as a final validation of all the choices made by the operator, as previously described (Fig. 10). It has to be noticed that this operation is easy to be carried out directly inside the "Digitised Shape" environment of CATIA, allowing modellers to perform fast work-in-progress accuracy controls and more refined final checks without the need to export the data to other software environments, representing a significative saving of time and resources if compared to the operations needed to

accomplish the same task at the time in which the model of the Main Spire was realised (Fassi & Parri, 2012).
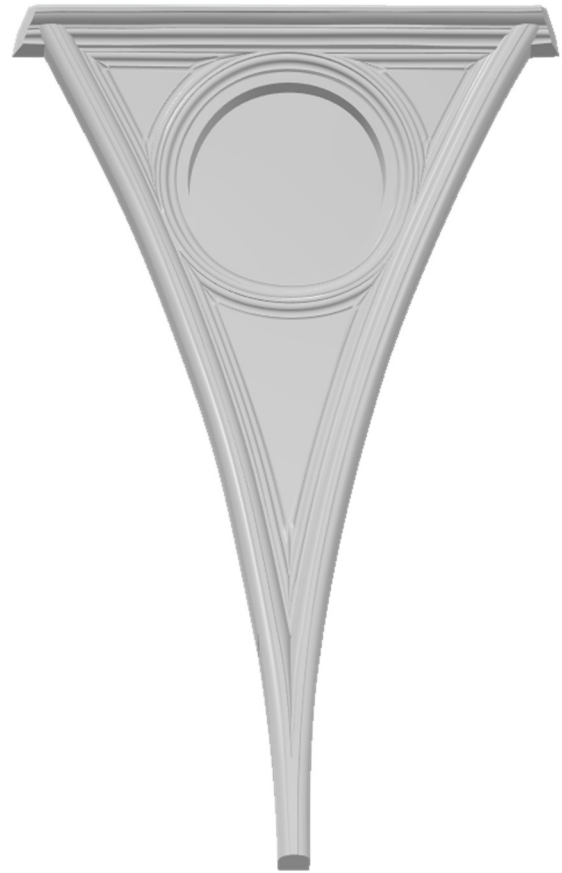

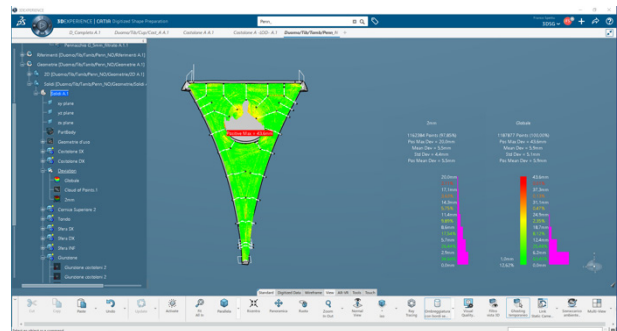**Figure 9**: The final modelled element, a pendentive of the dome, scale 1:50.

Figure 10: The dimensional verification performed inside the modelling environment.

5.3. Hybrid Modelling

For "hybrid model" (Brookes, 2017) is here intended an informative model that is constituted both by point clouds and solid and surface geometries. This kind of approach uses the point cloud as a self-standing object and not only as a reference for the profile extraction, being possible to manage information and attachments directly on the cloud object. The main advantage of this approach is that, once the global point cloud is accurately elaborated and segmented into the elements of the implemented structure, is possible to skip the time-consuming modelling phase, relying on the possible more accurate data representing the architecture, which is the point

cloud, instead of producing geometries that approximate the reality through selected profiles and software interpolation.

In the presented example, the hybrid modelling was applied to the statues of a capital (Fig. 11): a decorative element that is very difficult to be modelled and, on the side of the restoration yard, is managed as a whole. Each statue is a separated point cloud and has its own dedicated, informative sheet about status, condition and maintenance operations, as shown in the previous example in Section 4.4.
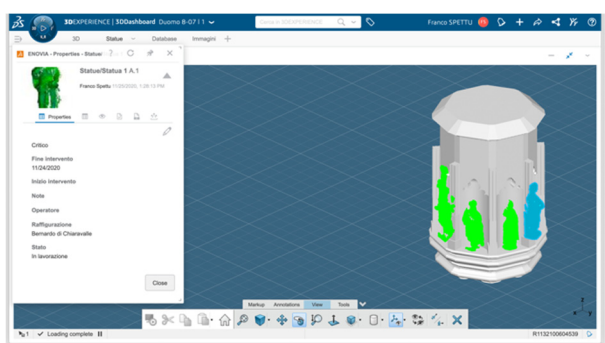

Figure 11: Example of how the point cloud was integrated with the solid models and how it is possible to enrich it with information.

The possibility of modelling when needed, when this operation adds value and information to the whole model, is believed as the most promising and encouraging aspect of the conducted test on the 3DExperience platform. It consents to focus the initial efforts and resources on the post-production of the survey data and in its general classification and segmentation in the established structure, being possible to subsequently integrate the whole model with solid and surface geometries, as an example, obtaining the marble block subdivision. This kind of adaptability is believed to be particularly useful in the field of Cultural Heritage.

5.4. Database creation

One of the most critical operations to be accomplished is to set the structure of the database and to populate it with the modelled three-dimensional objects, representing in a certain way the idea of translating all the data, knowledge, maintenance history and practices into an informative system able to gather such different and consistent information and to be proficiently used by the archivists, yard directors and operators.

The 3DExperience embodies a specific tool to accomplish this task, called "IP Classification", accessible through a web browser and with a textual interface that consents to build the database and manage the objects without visualising or render any geometry. The root of the database is named "Library" and can host an arbitrary number of nested subcategories, according to the needs. Each subcategory represents a level of the Cathedral subdivision as previously discussed.

This system acts as a central repository of all the information available for the Cathedral and consents to navigate through the monument structure and manage all the data: from the geometries and information attributes to the attached documents (Fig. 11). Every object, also

documents, has its lifecycle and all its versions are stored and available to the consultation: in this sense, the database allows the user to navigate inside the digitised knowledge of the Cathedral in spatial and chronological terms.

5.5. The user interface: front office

As "front office" (Fassi & Parri, 2012) is here intended the user-friendly interface created as a support for the maintenance operations in Milan Cathedral, used by the workers of the restoration yard to interact with the model for visualisation purposes and work on the informative part as the inspection and restoration activities are performed. This interface is intended to be used by not-specialised users and also on the restoration yard: it has to be easy to access and ensure usability even from portable devices.

The solution implemented as a feasibility test inside the 3DExperience platform is web-based and accessible through browser: every user has an account with specific permission and with a personalised interface, managed through dashboards and widgets. Dashboards are customisable panels that can be freely populated with widgets, specific applications for visualising, searching and modifying the data loaded in the platform. Once logged in, the user finds among his available dashboards the one suitable to his tasks and needs.

From the fruition interface, the user can visualise and navigate the 3D model or a portion of it, in order to identify the objects, as the blocks, on which he should intervene. The system allows to visualise the geometries, query the database and modify the data related to the objects inside the limits assigned to the user profile and make graphic and textual annotations on the shown geometries (Fig. 12).

6. Conclusion and future works

The long process of digitization of the Milan Cathedral began more than 10 years ago, starting from the knowledge and maintenance needs expressed by the VF. Comply with these needs means designing and implementing both on-site surveys and the processing and use of the data so that they are an effective support for the restoration office and yard. This implies using all the investigation techniques, keeping up with their evolution, and all the innovative and unconventional solutions, in the belief that the Milan Cathedral due to its history, its dimensions, and the uninterrupted operation of the maintenance yard, represents a unique challenge for the research in the field of digitisation in favour of built heritage.

The aim of this research is to experiment and consolidate various documentation techniques and test tools in order to create systems of knowledge, management, and use. "Documenting" and "managing" take on a very specific meaning. The documentation of the shape is necessary for the planning of maintenance activities, therefore suitable resolution and accuracy must be guaranteed. To manage the information that gravitates around the maintenance yard means dealing with an impressive amount of data that embodies a significant historical value: therefore, it is necessary to respond with a "time perspective" that does not only search for a solution to the immediate problems, but works to provide answers to

relevant questions. The management of Cultural Heritage as Milan Cathedral requires designing a flexible, customizable, and above all to build a long-lasting model (3D geometries and information) and data archiving system.

On the survey side, during the 10 years of work on Milan Cathedral, the frontier of research has moved from the acquisition of the data on the field to the processing and semantisation, with the significant contribution of AI and the derivative DL and ML procedures which have allowed data to be processed in significantly shorter times than what would have been possible doing it manually. Furthermore, the process eliminates the uncertainty linked to the interpretation of the data by the operator.

These first results suggest possible and unforeseen chances of using the data. The point models classified by the ML processes have been effectively employed with the Dassault system. The modelling tools that the platform offers are very effective, and the ability to create hybrid models and manage the life cycle of each object within the same environment makes the system extremely promising for an ambitious task as the complete reverse engineering of the Cathedral.

The close collaboration together with the technical office of the VFD has always stimulated the research activities and led to optimal and shared solutions to the encountered problems. An informative system for the entire Cathedral able to embody the data produced in recent years, to avoid duplicating the operations already done, to create connections between the different archives would act as a "hinge" around with the future operations and discussions will move.

Acknowledgements

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