

CONTRIBUTION OF PARAMETRIC MODELING IN THE INTERPRETATION OF DEFORMATIONS AND DISPLACEMENTS OF WOODEN TRUSSES

*Davide Prati, Ildeina Rrapaj, Giovanni Mochi**

*Alma Mater Studiorum - Università di Bologna – Bologna, Italy.

Abstract

The analysis of historical timber roofs is a topic widely dealt with in literature both in the disciplinary field of “theory of construction” and “construction technologies”, and in that of architectural technology and restoration. The specialist literature, however, has often simplified the constructive conception and evolution of these artifacts that, even when they stand still to date, show the signs of a long life, often hidden and little-known, even with regard to frequent changes over time. This paper aims to indicate a new methodological approach, based on generative algorithms, to attempt a more in-depth and transversal understanding of the behavior of these wooden structures, focusing on geometric surveying and constructive analysis. The developed method accelerates modeling procedures and it brings on new tools for analyzing these structural systems surveyed through Terrestrial Laser Scanning (TLS) devices.

Keywords

Construction history and preservation; Building heritage TLS survey; 3D modeling through generative algorithms; Reverse engineering applied to structural systems

1. Introduction

The analysis of the wooden roofing structures, historical trusses in particular, is present in scientific literature in many contributions, both in the disciplinary field of building science and construction technology, and in that of practical technology and restoration. Nevertheless, few studies systematically investigated the real behavior of these construction systems counting on experience and diagnosis in the field (Tampone, 1996) (Barbisan & Laner, 2000). This is justified by various factors, obviously including the fact that roofing structures are hidden and difficult to access, not attracting the attention of technicians and researchers, unless in case of severe problems of deterioration or obvious damage with consequences on people's safety. The roof is the area of the building most prone to deterioration and fire and is characterized by strong transformations and large substitutions over time.

The theme is therefore downgraded to an issue of minor importance for restoration, since the matter of study is no longer authentic or otherwise difficult to date. The interest is preserved only if these structures are left exposed and decorated or if they support valuable ceilings, for example

frescoed surfaces. One of the main reasons for this lack of attention, however, lies in the fact that wooden roofs are typically indeterminate structures, whose safety depends mostly on the materials' quality and on the characteristics of knots and joints. In other words, it pertains to the art of building, to the practice of carpentry and for this reason it eludes scientific and analytical interpretations, if not at the cost of large approximations.

The study proposed here is based on an accurate geometric and material survey of all constructive elements but above all, on the attempt to clearly understand the original implementation methods through the "rational" use of reverse engineering software and techniques. This contribution proposes the application of generative algorithms aiming at reconstructing a three-dimensional model of historical wooden trusses starting from a laser scanner survey. On the one hand, the analysis aims to give importance to this kind of constructive elements, neglected in the literature, identifying also new functional types, on the other it is used as an effective investigation protocol, with high

diagnostic capability due to the wide use of technologies.

2. *State of the art*

Studies on wide span roofing, especially trusses, are usually based on important textbooks (Emy, 1841); many classifications proposed in literature are the outcome of nineteenth-century technical sensitivity, that used to force complex and partly structurally undetermined systems into simplified and calculable schemes. In the recent past, some historians of architecture and construction used to identify structural systems types within these constructive systems, highlighting their behavior based on strongly simplified theoretical hypotheses (Munafò, 2002) (Laner, 2005) (Valeriani, 2006). Most of the technical solutions identified for possible consolidation, safeguarding and conservation policies, have often been based on these simplified hypotheses and on preliminary analyzes carried out with hurried surveys. The intervention logic was based most of the times on the idea of forcing the behavior of these structures into well-known or typical schemes.

Regardless of current approach to the problem of preservation of historical roofing structures, the research assumption is that digital technologies for surveying allow extrapolating new and original considerations that would be almost impossible following traditional methods of investigation, based on direct observation or on simplified architectural survey. If use of TLS for surveying complex architectural surfaces is not new and is matter of many researches in restoration field, rarer, or even absent, is its use applied to the study of hidden spatial structures such as wooden roofing. The outline hypothesis was to exploit the large amount of geometric data, which can be acquired by the TLS device as 3D point clouds, in order to read wooden trusses in detail and then gather specific and comparative information on their static behavior and on their conservation status.

Shaping of wooden trusses follows a very precise and often ignored construction practice, linked to the possibility of raising all elements up until the base of the roof, to readjust them, assembling them through other ancillary supports and fix them together using metal brackets. Nowadays the joining system of wooden elements has completely changed with the introduction of metal plates and the possibility of numerically

verifying each part of the artifact; then retracing the original logic of the junctions is a de facto non-trivial procedure. Palladian trusses, for example, are notoriously distinguished in classical and composed ones, but within these categories there are many diversifications. These depend on a series of factors: different ways of assembling the linear elements to form longer tie rods or rafters with larger cross section, more or less accentuated stiffness of the knots, due to the carving of notches and to fastenings, presence of more or less brackets and other characteristic details. (Guardigli, Lamborghini, Venturi, & Mochi, 2015) (Zamperini, 2013, 2015)

Large and detailed geometric information provides very interesting data to evaluate deformations, rotations and displacements of these structures, in order to identify their real behavior over time; such shape changes take place both at a local level, in the single truss, either at a global one, considering the entire roof behavior.

3. *The Research Protocol*

In order to systematize the analysis of these roofing systems, an investigation protocol has been set up and has been tested and developed by subsequent approximations after its application to different case studies. (Guardigli, Mochi, & Prati, 2017).

Many religious buildings, built between the 16th and 18th centuries, have been pinpointed in Bologna territory with pitched roofs made using wooden trusses. The most interesting among them are the Cathedral of San Pietro (Lamborghini, 2014), the church of San Salvatore Maggiore (Demattia, 2015), the church of San Giovanni in Monte (Gianvecchio, 2015), the Basilica of San Petronio (Malvezzi, 2015) and the Basilica of San Domenico (Manfredi, 2017). The choice to apply the protocol to these churches' roofing was due to the fact that these religious buildings were built almost in the same years and are all dimensionally significant.

The protocol immediately took on definite and precise traits, so much so that it can be graphically summarized in a synoptic diagram that represents its different phases. (Fig. 1) This method continually benefits from feedback from the case studies still in progress, showing also good adaptability to different contexts. The protocol includes an acquisition step followed by the digital rendering of the acquired data. This last step provides many outputs (photos, drawings, graphs

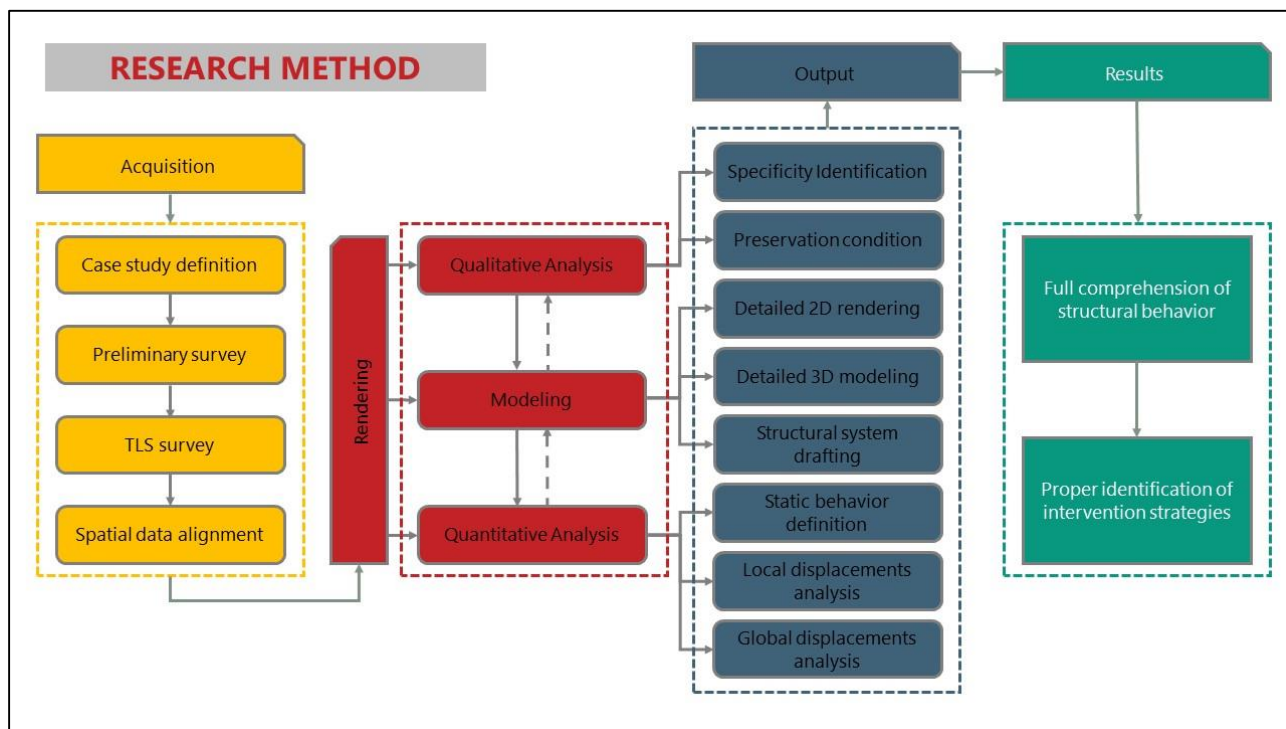


Fig. 1: Synoptic diagram summarizing the stages of the operational protocol. Different colors are used to distinguish the phases. The yellow part represents the data acquisition phase through laser scanner 3D, the red part represents the map rendering and analysis of the point cloud data, the blue part includes the output of the previous step and the green part represents the achieved results.

and models) that constitute the operative tools to define and correctly interpret the behavior of the constructive systems studied. Results interpretation therefore allows us to suggest the most coherent design solutions, disengaging them, where necessary, from usual and standardized techniques (Prati, Mochi, & Guardigli, 2016).

Although some significant results were obtained applying the described method, several critical issues were found, mainly regarding the step in which simplified 3D models were generated (rendering). Vectorization of orthophotos strongly depends on the operator and has a low degree of repeatability and precision. Given the size of these artifacts, moreover, it is not possible to resort to the automatic generation of meshes, since the point clouds are largely incomplete and extremely articulated.

To overcome these difficulties, it was considered suitable to review and improve this rendering step within the research protocol.

4. The Case Study

In order to develop and test a new approach to rendering step, with a new model generation method, a case study was chosen among those already investigated. In this way it was possible to compare the obtained results, so as to evaluate any improvements in terms of precision and accuracy, in relation to time spent and process automation. (Kaylan et al., 2016) (Bello Caballero et al., 2017)

Among the available case studies, the chosen one has been the church of San Domenico, in particular the portion of the roof corresponding to the choir area.

This is the patriarchal church of the Order founded by Domenico di Guzmán¹, who settled in the convent of San Nicolò delle Vigne in 1219. Here, between 1220 and 1221,

¹ Saint Dominic (Spanish: Santo Domingo), also known as Dominic of Osma and Dominic of Caleruega, often called Dominic de Guzmán and Domingo Félix de Guzmán (8 August

1170 – 6 August 1221), was a Castilian priest and founder of the Dominican Order. Dominic is the patron saint of astronomers.

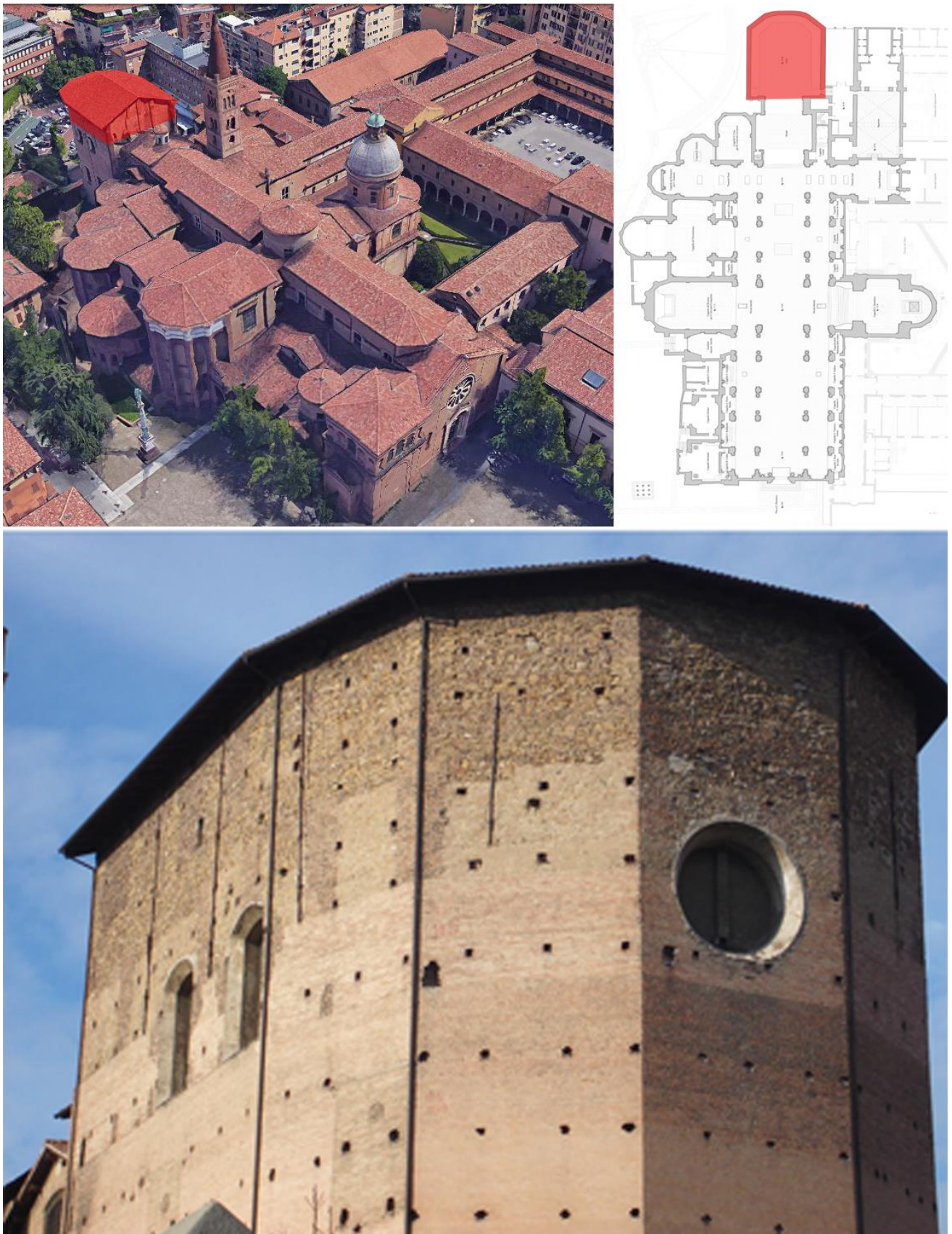


Fig. 2: top left - View of the convent of San Domenico (source Google Earth®)
top right - Planimetric scheme of the church (source Eng. Anna Lisa Grandi)
bottom - Picture o the choir's roofing from the outside shot at ground level (author)

San Domenico personally presided over the first two general chapters intended to clarify the fundamental elements of the Order. Still here, on 6 August 1221, Domenico died and was buried behind the altar of San Nicolò.

The old convent, starting from 1228, grew larger with demolition of the apse and expansion of the existing nave. The construction of the new basilica of San Domenico was almost completed in 1240 when the sober Romanesque front was accomplished. Pope Innocent IV consecrated the basilica on October 17th, 1251.

The church and the annexed convent underwent further enlargements and reworking in the fourteenth century, with the addition of some chapels and a bell tower and accumulating over time a vast collection of works of art by major artists of the time. (Fig. 2)

The stylistic composition of the Basilica of San Domenico exhibits, before visitor's eyes, as a set of shapes and colors of many different artistic currents that have developed since 1300 onwards. The Romanesque facade, Gothic and Renaissance chapels, the Baroque apse, the interior decorated according to Bolognese Baroque style and the contrasting colors of the terracotta exterior with the white plaster interior, make this complex religious building the "custodian" of many centuries of art history and "witness" of the lords' changing tastes between different ages.

In the eighteenth century, however, an important transformation of the church takes place, in an almost involuntary manner. In the year 1727, Pope Benedict XIII wanted to renew the roof of the rectory that was in bad condition, but also cover the ceiling with vaults along the side aisles. Works were commissioned to Carlo Francesco Dotti², a Bolognese architect, who took on the task with great care. Dotti's dedication made it possible to complete an even larger renovation work than expected.

In short, the project consisted of completely raising the roof, considered unsafe, on one and only level, trying to give a unitary appearance to the whole building, preserving the ancient structures and chapels of the Holy Rosary, of San Domenico and of San Pietro Martire. In particular, the choir and chapels roofs were judged in a very bad state.

² Carlo Francesco Dotti was born and died in Bologna, where he became one of the main protagonists of the late Baroque style.

Like in all great religious buildings of that period, there were problems related to the retrieval of materials, especially wood that had to be used for the new roof. On July 4th, 1727, the Prior Father commissioned the merchant Pietro Chiosi to find the necessary woods.

Chiosi went five times to Ferrara, Ostiglia, and Polesella and finally to Verona where he found everything he was looking for. The shipment was sent by river to Pontelagoscuro, by horse-drawn wagon to Malalbergo and again by river to Bologna, arriving in the city between September and October 1727. During summer, however, works did not stop waiting for wood, but the roof was uncovered, dismantled and finally the supporting walls were raised by 4 meters. In order to raise walls, some arches of the church nave were reinforced with pillars. (Fig. 3)

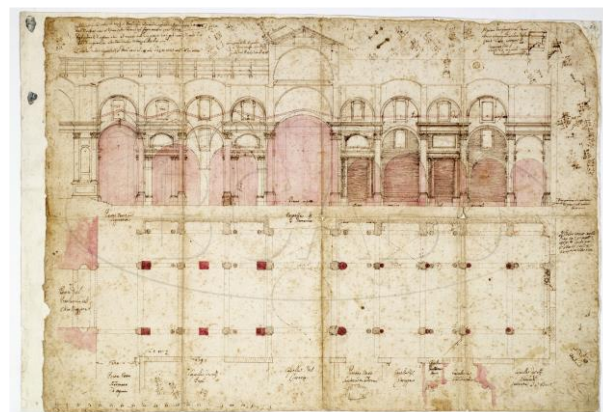


Fig. 3: Blueprints regarding the modifications that Dotti intended to apply to the San Domenico church. The dotted lines represent the structure before the modifications and the red part indicates the position of the pillars, columns and arcades of the previous San Domenico church. (Source: *Archiginnasio di Bologna, Raccolta Gozzardini, Cart. Gozz. 27, n. 29*)

Towards the end of November 1727 works on the raising of the walls and on the central nave roof were completed. A few months later the work on the roofing of the presbytery and of the transept ended, while those of the choir ended in the middle of September 1728. The delay for the choir roof was due to the search for 20 meters long wooden tie rods, intended to connect from one wall to another the choir trusses, in order to act as a bridge and as support for the whole roofing. Nine

His most famous work is the Sanctuary of the Madonna di San Luca, Bologna, which is raised on a hilltop above the city, consisting of a church topped by an elliptical dome, with extensions leading to two pentagonal pavilions

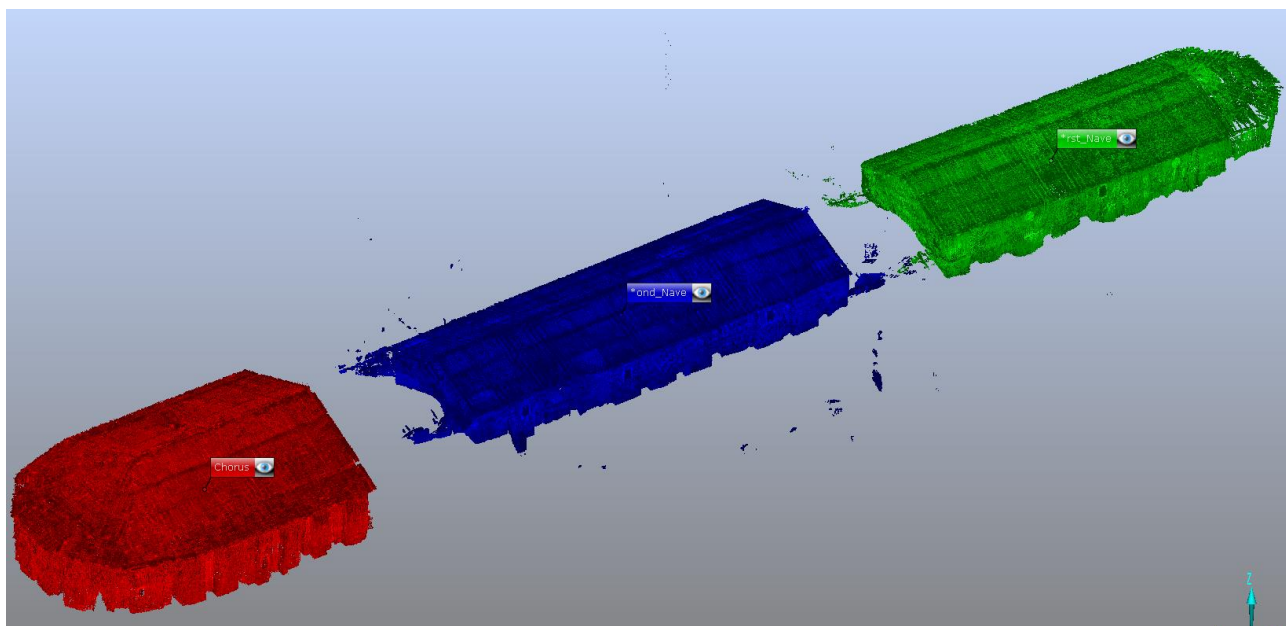


Fig. 4: Point cloud of San Domenico church; the green color indicates the first nave, the blue color the second nave and the red color indicates the Chorus which is the part of the church analyzed in the current work.

giant fir trees were bought, grown up in Bolzano and arrived in Bologna via Verona (Venturino, 2015).³

These new trusses of the choir, made by Dotti, have a configuration of Palladian queen post truss with side queen posts that build up the joint with the straining beam. The under-rafter stops at the level of the straining beam while the upper-rafter continues up to the ridge ending in a small central connecting king post. There are 8 Palladian trusses, 3 of which are lowered to create a hipped roof with a slope of about 22 degrees. These trusses have a wide span of more than 16 meters, they are about 6 meters high and stand at an interaxis average distance of 3 meters along the main axis of the roof. (Manfredi, 2017)

³ These information are confirmed in the book *Memorie Domenicane* by P. Alce Venturino (ed. Firenze, 1969), *La chiesa di San Domenico in Bologna rinnovata da Carlo Francesco Dotti negli anni 1727-1733*, fasc. II, pp 150-168. The documents, which guarantee the authenticity of what was written by Alce Venturino, are kept in the archive of the convent of San Domenico. In particular, they are part of the collection *Fabrica Chiesa* (numbered files from 9 to 16), which stores books of expenditure, receipts, lists, etc. from 1728 to 1732.

There are also two Dotti's writings about the renewal of the Church, precisely:

Informazione sopra l'idea del Rimodernamento della chiesa di S. Domenico di Bologna - 1728 (= Idea);

Informazione del principio e proseguimento della fabrica per la rimodernazione della chiesa di S. Domenico di Bologna - 1730 (= Principio).

The choir roofing structures' circumscription and their easy accessibility allowed to carry out a good survey campaign. In addition, the simplicity of the trusses' static scheme, their authenticity but also their remarkable construction quality and, last but not least, the historical importance of the entire building, suggested to choosing these elements as test to the research protocol improved with a new model generation method.

5. The Model Generation Procedure

Starting from the point cloud obtained from laser scanning⁴, it was decided to experiment a new way for its 3D modeling. This decision is justified by the impossibility of creating meshes directly from the point cloud for many reasons, such as the relevant size of the studied artifacts,

According to the author of the book, the two Dotti writings were published as document number XXXI in the book: BERTHIER J.J.d.P., *Le tombeau de Saint Dominique*, Paris.

⁴ The entire TLS survey of San Domenico's roofing has been carried out with a FARO CAM2 FOCUS 3D laser scanner using a targetless approach. The survey campaign took 3 working days and it was necessary to shoot 91 scans with a resolution of 12mm/10m and a quality filter of 3x in order to get the whole roofing. The survey of the choir roofing needed 30 out of 91 scans and the alignment was performed using an interactive Cloud to Cloud registration. With a medium overlapping between scans of 22,3% it was possible to achieve an extremely accurate alignment with standard deviation between correspondent points of 2.5 mm and a maximum deviation of 3.8. The whole point cloud counts over 390 million points. (Scene 7.1 User's manual, 2017)

the incompleteness of scan data in the hard to reach areas, the preliminary work required for editing the point cloud and finally the long processing times. (Fig. 4)

In the previous method, it was necessary to perform "vectorizing" operations of frontal orthophotos of each truss, from which to draw 2D drawings and 3D models. In order to use reverse engineering software with complex objects such as trusses, it was initially thought of using spatial data to create simplified 3D models through a "rectification" of rods and an identification of the "ideal truss". This ideal truss aims to be the one that best represents the initial condition, undeformed, as well as put in place by original builders. This procedure was supported by some simplifying hypotheses such as the horizontality of supports, the verticality of posts and the absence of rotations in the rods and allowed to generate a single 3D model of the standard truss for each case study. In order to be used for comparison, this ideal model would then have to be re-aligned with the corresponding analyzed point cloud portion. It was then necessary to identify, within the software, at least three corresponding points on linearly independent orientations. Subsequently it was necessary to perform an optimization command in order to minimize the average square deviations to guarantee the maximum degree of overlap between the ideal model and the point cloud.

To avoid operating with excessive approximations, it was decided to transform the point cloud into 3D models using parametric modeling tools such as generative algorithms.

These algorithms, once created for a single truss, allow to automatically generating 3D models of all trusses, changing only input parameters. This procedure allows saving a considerable amount of time and eliminates many of the inaccuracies identified by adopting the previous vectorization method. (Prati et al., 2016)

5.1. 3D Basic Model

Using a repeatable methodology, applied to different case studies on the same subject, makes results comparable basing on a scientific and not empirical approach. The survey is performed with a FARO CAM2 FOCUS 3D laser scanner. This device, light and handy, allows on-site scanning with a simple photographic tripod, making survey campaigns very fast. Moreover, the use of a targetless technique minimizes the preparatory

activities within scanned locations and the dead time between a scan and the next one.

Once aligned all scan positions with FARO SCENE software the project point cloud is created. A part of this, the one representing the truss object of study, is extracted, and it is sectioned close to the knots through proper arrangement of a few clipping boxes. Size and orientation of clipping boxes varies according to the sectioned element, remaining as far as possible orthogonal to each beam itself. (Fig. 5)



Fig. 5: Examined truss extracted from the Chorus point cloud. The red rectangles indicate the clipping boxes used for the sectioning of the cloud. Such clipping boxes measure 1 cm of thickness, which means they isolate the points contained in 1 cm, they are located in proximity of the knots between the elements and oriented perpendicularly to them.

These sections are exported as orthophotos in a 3D modeling software, Rhinoceros. Exporting takes place at the original coordinates of the section without the need to create additional reference systems or to make further alignments. This task is done entirely by keeping fixed the global point cloud's reference system. (Fig. 6)

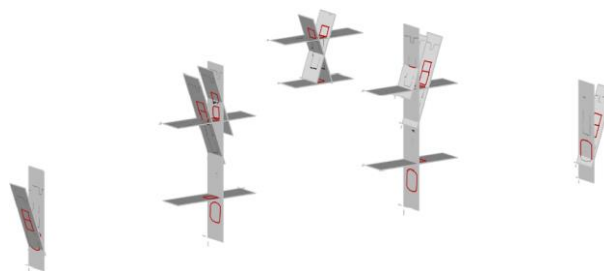


Fig. 6: Orthophotos of the clipping boxes exported in 3D modelling software. The traces of the sections obtained from these orthophotos are highlighted in red.

After exporting orthophotos of all sections, their vectorization is performed manually. This is the only non-automated operation within the present modeling method.

In fact, after obtaining section curves, the generation of a 3D model is performed through a process that takes advantage of those generative

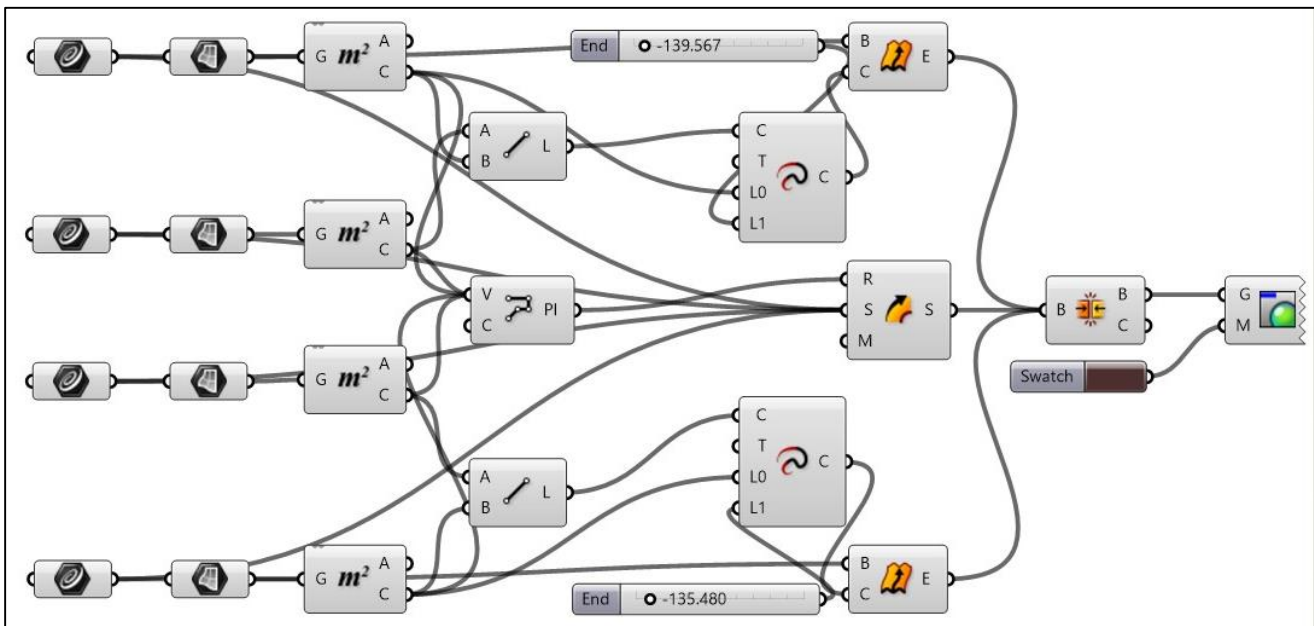


Fig. 8: Modelling process of a truss element created with Grasshopper’s generative algorithms. Each box represents an operation with an input on its left and output on its right. The connections between the boxes indicate the order of the operations. By connecting the outputs of an operation to the inputs of another operation, the result model is automatically generated and it depends on the initial parameters set manually.

algorithms mentioned previously. The aim is to create a method that accepts the vectorized sections as input and extracts the 3D model of each truss as output.

The model generation process is defined using Grasshopper, a Rhinoceros 3D software plugin. First of all, section curves previously obtained are implemented as input parameters. This means that the final output of the entire algorithm will depend exclusively on inserted curves. (Fig. 7)



Fig. 7: Surfaces created by the algorithm from the sections obtained previously from the orthophotos.

In Figure 8, each box corresponds to one of the implemented operations. Starting from the left, the boxes represent the section curves that are the input parameters. Then the algorithm transforms the implemented curves into surfaces, operation represented by the next column. Once identified surfaces surrounded by input curves, the algorithm calculates their area and the center of gravity of each of them and then draws a polyline joining the newly identified barycenters. (Fig. 9)

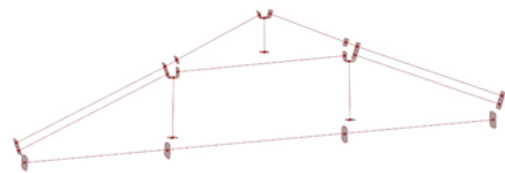


Fig. 9: Output of the algorithms implementing the identification of each section’s barycenter and their connecting with polylines.

Finally, the algorithm extrudes all sections along these axes defined by barycenters, thus obtaining the 3D profile of each beam. To create knots, section curves are extended along their barycentric axis until they intersect another crossing beam.

The result of this process is a 3D model representing the truss rendered with a limited number of sections. Number and position of the sections used has been decided in order to have the best-fitted 3D model with the lowest number of sections. Creation of clipping boxes, orthophotos and the subsequent vectorization, in fact, represent the most time-consuming steps of the whole method. As a result, using fewer possible sections strongly affects the quickness of the proposed method. (Fig. 10)



Fig. 10: Result of the modelling process; the algorithms implement the sweep of each section through the binary defined by the polyline connecting their barycenters.

To verify the degree of compliance of the rendered model with the surveyed point cloud, a comparison of these two elements is carried out using a reverse engineering software, Geomagic Control X. The same software detects and reports in a chromatic scale distances between the points of the point cloud, considered as reference object, compared to the 3D model, considered as test object. Furthermore, it is possible to extract summary reports indicating the percentage of points within the nominal overlap threshold of the two compared objects.

The two highlighted columns contain the points within the threshold ± 5 mm whose deviation is considered non-significant, then treated as correctly overlapping points. Adding the point's percentage of both the negative and positive threshold the total degree of overlap between point cloud and 3D model is equal to 73.63%. (Rrapaj, 2018) (Fig. 11)

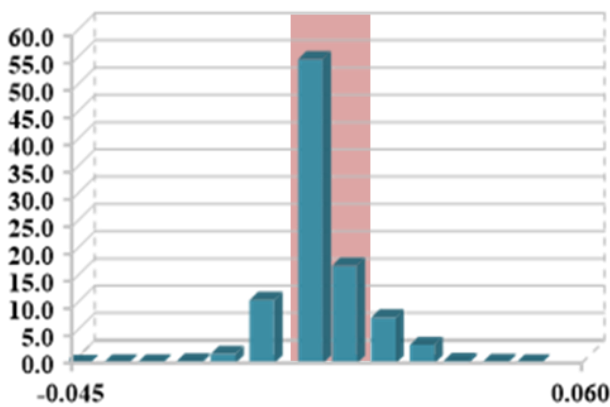


Fig. 11: Graph indicating the distribution of the deviation of the point cloud from the base model. The highlighted columns represent the points with a very small deviation so that they can be considered as perfectly overlapped.

5.2. Inferred 3D models

After defining the basic 3D model as described above, it is possible to proceed with the construction of a 3D model with an even higher degree of overlap to the point cloud, referred to as

detailed 3D model. Furthermore, it is possible to define another virtual 3D model, only for study purpose, representing a reasonable original truss condition at construction time, called the ideal 3D model.

The detailed 3D model is rendered with the aim of creating a 3D object comparable to the starting point cloud without losing essential metric information. In this way, it is possible to use the detailed model itself instead of the point cloud for all next analysis to reduce processing times and improve results reliability. To obtain greater precision, it is decided to increase the number of vectorized sections used as input parameters in the modeling process described above. By simply using the same algorithm with which the basic 3D model was created, once made appropriate changes related to the increase of the sections considered, the new detailed 3D model is obtained automatically. (Fig. 12)



Fig. 12: Increasing of the sections of the point cloud in order to create a more detailed model of the truss.

By comparing the detailed model with the point cloud, as it has been done with the basic model, it is possible to obtain numerical entity of the degree of overlap. In this case, the new model is approximating the cloud to 91.55%. (Fig. 13)

This is considered satisfactory approximation; it seems therefore allowed to replace the point cloud with this model in all following analysis steps. However, having created a process able to automatically generate the 3D model after inserting vectorized section curves, it is theoretically possible to detail the model more and more, when necessary, in order to further increase its approximation to the point cloud at the expense, obviously, of processing time.

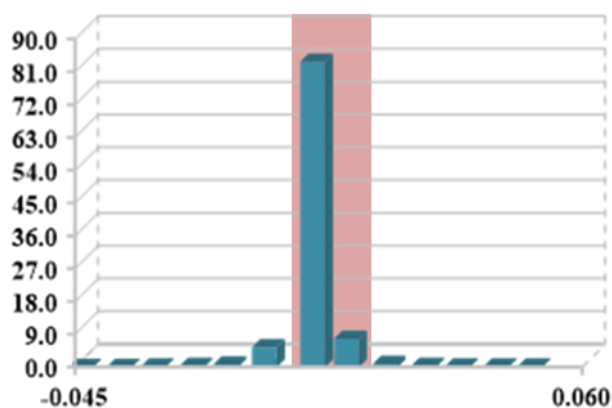


Fig. 13: Graph indicating the distribution of the deviation of the point cloud from the detailed model

The ideal 3D model, on the other hand, is conceived with the aim of creating an ideal comparison model useful for analyzing the current static condition of the truss in such a way as to be able to highlight all undergone changes during its service life. Achieved data are used to interpret the behavior of the structure in terms of displacements and deformations. While not having available data on the truss original condition at the time of installation, a series of theoretical assumptions had to be made in order to proceed with the construction of this model. The basic principle is to bring the basic 3D model, as defined in paragraph 5.1, to a pre-condition without displacements and deformations. In other words, to what it is supposed to be the original condition at construction time.

First of all, all members forming the truss are brought into a single vertical plane passing through both bearings of the tie beam. This decision is justified by the fact that bearings of the tie beam are comparable to fixed points. It is assumed, therefore, that the displacements occurred in correspondence of bearings are negligible and consequently that the vertical plane of the truss passes through these points. The orthogonality of this plane is assumed by virtue of the fact that the truss was supposed to be built perfectly planar.

Once identified this ideal vertical plane passing through both bearings of the truss, within the algorithm it has been created a new projection process of all the vectorized barycenters and their subsequent translation in their new position on the plane. This change of position of the barycenter brings along the entire vectorized section. In this way, a perfectly planar structure is modeled, which highlights already occurred displacements

from the plane. Figure 13 shows how the basic 3D model, in gray, tends to come out from the plane defined by translated vertical model, in orange, highlighting rotations outside the truss plane. (Fig. 14)

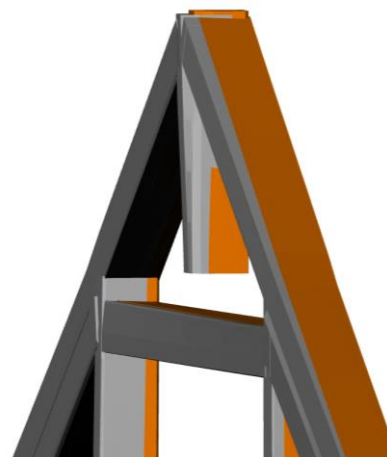


Fig. 14: Highlighting of the structure's displacements by overlapping the base model, represented in grey, with the one obtained from the projection of the sections to the perfect vertical plane of the truss, represented in orange

Next, it has been carried out the rectification of each truss member. Main purpose of this step is to create a 3D model that allows highlighting further deformations and displacements, especially bending phenomena, not identified by previous step. As usual, this process is carried out using Grasshopper algorithms. First, the construction of each member is made with only two extremity-vectorized sections in order to obtain perfectly straight elements. In order to better rectify all members, in addition to drawing them with only extremity sections, they have been also rotated as to reach mutual orthogonality. This step is carried out aligning the barycenter of vectorized section at the free extremity of the member, with the straight perpendicular line passing through the barycenter of vectorized section at the fixed end of the same member. Figure 15 clearly shows how this operation discriminates different members of the rectified 3D model compared to those of the basic 3D model; highlighting any rotations occurred. (Fig. 15)

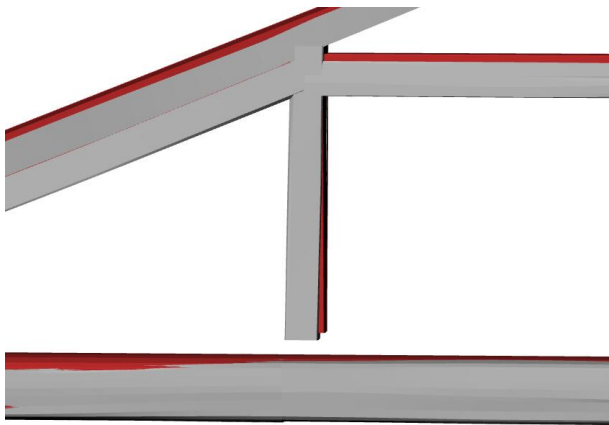


Fig. 15: Highlighting of the structure’s deformations by overlapping the base model represented in grey with the one obtained from the projected and linearized elements represented in red.

The exposed method therefore allows the creation of different procedures capable of generating both a detailed 3D model, which approximates metrically the point cloud over 90%, and an ideal 3D model that represents the best possible reconstruction of the undeformed truss. (Rrapaj, 2018)

6. Data Analysis

Once the representational models of each truss current situation (detailed 3D model) and of each truss undeformed original situation (ideal 3D model) have been rendered, they are overlapped to highlight their dimensional differences. As previously mentioned, this step is carried out using the reverse engineering software Geomagic

Control X that is able to examine and subsequently graphically report, in chromatic scale, the deviation between every corresponding points of compared trusses. Minimum and maximum deviation threshold to be detected is set manually, in the chromatic scale, in order to have a better indication about the order of magnitude of dimensional differences between trusses.

Geomagic Control performs a comparative analysis to evaluate the deviations between the external faces of the solid geometric model and the point cloud. Graphical representation through the most appropriate chromatic scale makes clear the entities of the displacements. It is possible to select any position on every member of the truss in order to highlight locally the numerical value of deviations by means of a 2D graphical representation. This interpretation provides both qualitative and quantitative information and eases an accurate and widespread understanding of all movements and deformations that each truss underwent over time in the entire roofing. Moreover, lowerings and rotations of the king and queen posts can be analyzed and highlighted locally, as well as torsional phenomena or rotations of the tie beams, lowering of bearings and bending of rafters, and eventually deformation phenomena withstood by the whole roofing.

Comparisons can be made between two complete 3D models (Fig. 17), and on 2D projection planes selected by the user depending on the kind of truss member and on the type of deviations that have to be magnified. The software itself allows, in addition to the deviations graphical

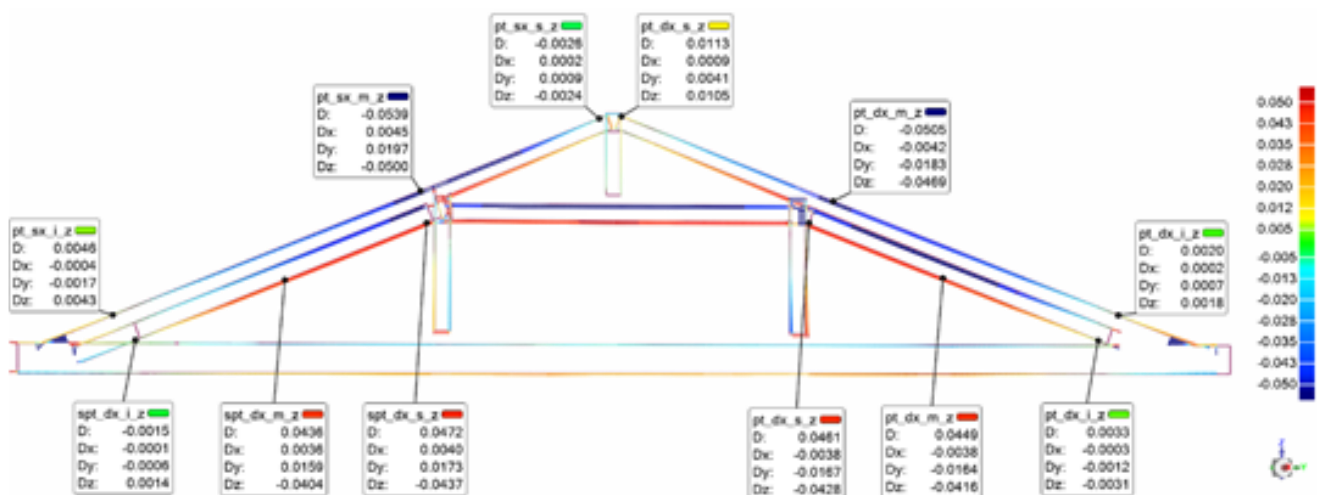


Fig. 16: Overlapping of the detailed and theoretical model; two-dimensional section on yz plane with annexed annotation of the displacement values on the most significant control points. The deep blue and red colors represent the most relevant displacement that goes from 5 to 7 cm.

representation, their precise quantification using control points. By using the annotation tool, it is possible to report the exact value of the distance measured between the corresponding points of the two compared models and its decomposition along the x, y and z axes. (Fig. 16)

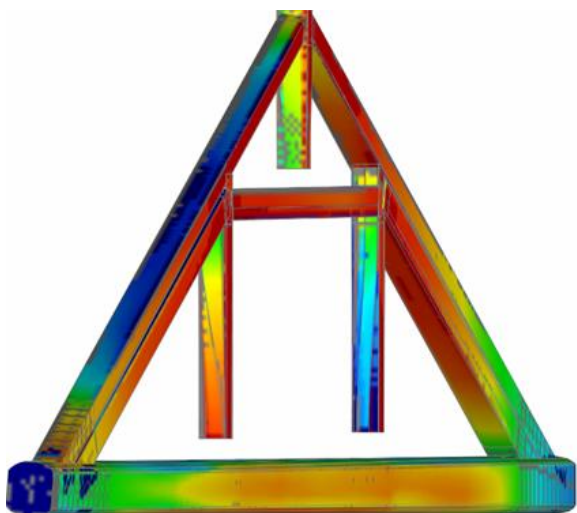


Fig. 17: Three-dimensional representation of the displacement observed by overlapping the detailed and theoretical model. The green color represents minimal displacement (± 5 mm) and the red represents displacement over 5 cm

Many types of movements or deviations can be highlighted by conveniently choosing these

control points along some truss members constituting each truss under investigation. Precisely because of the way the ideal 3D model was modeled, it is possible to quantify, with enough precision, bending phenomena on principal rafters and on the tie beam; rotations of posts in the truss plane, displacements outside the truss plane of rafters and posts.

Collected numerical data can be ordered in specific tables in order to obtain an overall overview of all values recorded through described analyses. Data collection thus becomes a very important step to ensure acquired information traceability and, once this information has been properly systematized, it becomes the tool through which to interpret correctly the behavior of these structural systems from a quantitative and not only qualitative point of view. (Tab. 1) Numerical data can also be reorganized into diagrams, graphs or inferred tables in order to explain better the behavior of many trusses members. (Fig. 18)

Tab. 1: Displacement values on the most significant control points of the examined element.

Control Points			Inf.	Mid.	Sup.	Inf.	Mid.	Sup.
TRUSS MEMBER			Left Rafter			Right Rafter		
TRUSS 1	Displacements [m]	Δx	0,0096	-0,0023	-0,0680	-0,0128	-0,0303	-0,0713
		Δy	-0,0019	0,0005	0,0132	0,0025	0,0059	0,0139
		Δz	0,0043	-0,0500	-0,0024	0,0018	-0,0469	0,0105
TRUSS 2	Displacements [m]	Δx	0,0120	-0,0005	-0,0262	0,0091	-0,0166	-0,0329
		Δy	-0,0021	0,0001	0,0046	-0,0016	0,0029	0,0058
		Δz	0,0007	-0,0368	-0,0026	0,0000	-0,0423	-0,0013
TRUSS 3	Displacements [m]	Δx	0,0167	0,0039	-0,0640	-0,0097	-0,0247	-0,0658
		Δy	-0,003	0,0186	0,0115	0,0017	-0,0209	0,0118
		Δz	-0,0014	-0,0469	0,0028	0,0016	-0,0526	-0,0105
TRUSS 4	Displacements [m]	Δx	-0,0019	-0,0187	-0,0101	0,0045	0,0171	0,0046
		Δy	0,0003	0,0034	0,0018	-0,0008	-0,0031	-0,0008
		Δz	-0,0023	-0,0541	-0,0017	-0,0008	-0,0478	-0,0013
TRUSS 5	Displacements [m]	Δx	0,0055	-0,0195	-0,0406	0,0054	-0,0117	-0,0094
		Δy	-0,0010	0,0035	0,0073	-0,0010	0,0021	0,0017
		Δz	0,0020	-0,0598	0,0010	0,0012	-0,0700	-0,0015

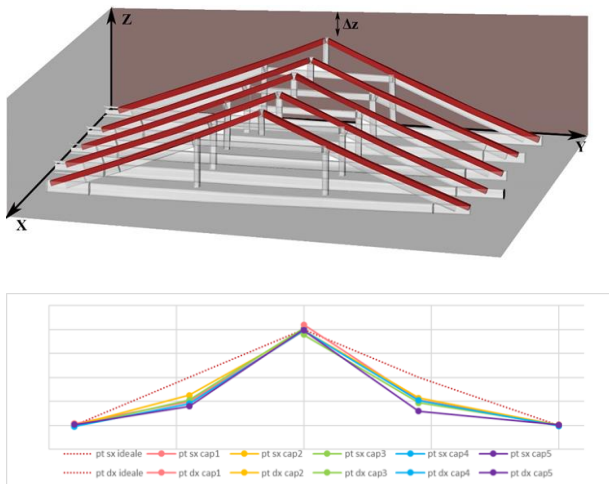


Fig. 18: Graphical representation of the numerical data contained in the overhead table. In the second image, the red dashed lines indicate the ideal condition of the rafters with no deformations experienced, whereas the colored lines represent the actual condition of the rafters. In the first image are highlighted in red the examined elements of the truss and the plane from which they are represented in the graph.

The main advantage of modeling wooden trusses through generative algorithms lies in the fact that, having carried out the whole process for the typical truss, it is possible to reiterate it for all the others trusses of the same type with a considerable advantage in terms of time. In fact, it is only necessary to input the new vectorized section curves to automatically generate all the subsequent 3D models. In this way, it is possible to carry out an overall analysis of all trusses that form the entire roof as illustrated above and to have a better understanding of the overall behavior of the structural system as a whole at the same time. (Fig. 19)

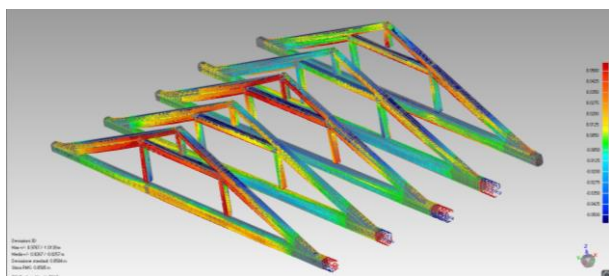


Fig. 19: Analysis of the whole attic in order to evaluate the global behavior of the previously examined structures. The presence of red coloring in the first three trusses means the elements have experienced displacements towards the existing wall

7. Conclusions

The analysis shows that the trusses in the choir roofing of the Basilica of San Domenico are in good condition, confirming with numerical data from the previous qualitative analysis. (Manfredi, 2017) Moreover, the new numerical quantification, in support of qualitative deviation data, makes it possible to compare these displacements and deformation with the safety limit values imposed by current regulation. In this way, the identification of truss members in structural problematic or risky condition becomes more precise and reliable.

This work, however, is not limited to the analysis of trusses in this particular case study but aims at the implementation of an equally efficient method applicable on every other similar type of wooden trusses into other roofings. The goal was to create a procedure that was as independent as possible from the operator who performs it.

Having an effective and efficient method available is an important goal, as it allows a more accurate study and understanding of these structures in a relatively timesaving and cost saving way. In this way, the technicians and researchers interest could be re-raised on a somewhat neglected theme. With these new available tools, it becomes possible to design targeted and effective restoration interventions.

The most significant result of what has been presented consists in the substitution of the manual work of rendering a 3D model with a process defined by generative algorithms. This substitution has brought a significant reduction in processing time and reduced the arbitrariness and inaccuracies due to the subjective considerations of the operator in the modeling phase. The choice to use the vectorized cross-sections as a basis for the generation of 3D models has prevented inaccuracies due to the vectorization and extrusion of the frontal orthophotos. 3D models rendered in this way respect much better the morphological and spatial characteristics of the original structural systems, reaching an approximation to the survey point cloud up to 90%.

In addition to the rendering of a relatively detailed 3D model, it has been possible to define a procedure able to generate automatically many other 3D models by simply varying input parameters that seems to be an effective procedure for all structural systems with

characteristics similar to wooden trusses. This means the possibility to render, in a short time and with good approximation, 3D models of large objects starting from a mere point cloud, even if incomplete and not totally closed.

Another very important result was achieved on the creation of the ideal 3D model that represents the truss at time zero that is without deformations and displacements. This model, crucial in the analysis of the behavior of the structure, has been rendered through a generation process similar to the detailed 3D model, based on well-founded theoretical assumptions. The aim was to bring back the basic model in the conditions in which it should have been at construction time. In other words, remodeling perfectly linear and coplanar truss members, as they normally should be built. In this way, the ideal 3D model is always reconstructed starting from the point cloud of each truss analyzed and it is generated by a procedure made of algorithms that works backwards, so as to bring the model back to an undeformed configuration. Operating like this, the ideal 3D

model of each truss is obtained at the same time as the detailed 3D model.

Compared to previous works, where the ideal model was rendered as the average of all the surveyed trusses, the new method has eliminated most of the inaccuracies due to these approximations. Consequently, analyzes results can be considered most reliable and easily interpretable. Moreover, the substitution of the point cloud with the detailed 3D model makes it possible to perform comparisons only between two 3D models, involving not only a drastic reduction in calculation time, but also much clearer and better quantifiable results.

Good results obtained suggest applying this new method to other case studies already analyzed, in order to confirm both the best effectiveness in terms of quantitative definition of deviations and of evolution interpretation over time of wooden trusses, both the best efficiency in terms of working times and accuracy achieved.

REFERENCES

- Barbisan, U., & Laner, F. (2000). *Capriate e tetti in legno: progetto e recupero: tipologie, esempi di dimensionamento, particolari costruttivi, criteri e tecnologie per il recupero, manti di copertura*. Milano: FrancoAngeli.
- Bello Caballero, L., Mezzino, D., Federman, A., & Santana Quintero, M. (2017). From field work to deliverables. Experiences on the tin house courtyard documentation. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W5*, 77–81. <https://doi.org/10.5194/isprs-archives-XLII-2-W5-77-2017>
- Émy, A. R. (1841). *Traité de l'art de la charpenterie*. New York: Avanzo. Retrieved from <http://archive.org/details/traitedelartdela01mygoog>
- Grandi, A. L. (2008). *Studi storici recenti e interpretazioni delle fasi costruttive della chiesa di San Domenico in Bologna finalizzate ad un restauro consapevole* (Master's Degree Thesis). Alma Mater Studiorum - University of Bologna, Bologna.
- Guardigli, L., Lamborghini, S., Venturi, L., & Mochi, G. (2015). Historic Timber Trusses in Europe. The Case of St. Peter in Bologna. In *Fifth International Construction History Congress* (Vol. 2, pp. 449–456). Chicago: Construction History Society of America.
- Guardigli, L., Mochi, G., & Prati, D. (2016). Indagine sulla costruzione delle capriate lignee a Bologna tra il xvi e il xvii secolo. In *Colloqui.AT.e 2016 M A T E R (i) A Materials | Architecture | Technology Energy/Environment | Reuse (Interdisciplinary) | Adaptability* (pp. 715–724). Palermo: Gangemi.
- Kalyan, T. S., Zadeh, P. A., Staub-French, S., & Froese, T. M. (2016). Construction Quality Assessment Using 3D as-built Models Generated with Project Tango. *Procedia Engineering, 145*, 1416–1423. <https://doi.org/10.1016/j.proeng.2016.04.178>
- Lamborghini, S. (2014). *Le capriate della Cattedrale di San Pietro a Bologna. Analisi statico-costruttiva e individuazione dei criteri d'intervento* (Master's Degree Thesis). Alma Mater Studiorum - University of Bologna, Bologna.
- Laner, F. (2005). *Tecnologia del recupero delle strutture lignee*. Mestre: Flap.
- Malvezzi, T. (2015). *La copertura della Basilica di San Petronio a Bologna; dall'analisi statico-costruttiva all'individuazione di criteri d'intervento per la manutenzione* (Master's Degree Thesis). Alma Mater Studiorum - University of Bologna, Bologna.
- Manfredi, C. (2017). *Le capriate della basilica di San Domenico a Bologna. Rilievo, analisi e valutazioni statico-costruttive*. (Master's Degree Thesis). Alma Mater Studiorum - University of Bologna, Bologna.
- Munafò, P. (2002). *Le capriate lignee antiche per i tetti a bassa pendenza: evoluzione, dissesti, tecniche di intervento*. Firenze: Alinea.
- Prati, D., Mochi, G., & Guardigli, L. (2016). Contribution to the knowledge of wide span wooden roofing in the area of Bologna. *Tema: Technology, Engineering, Materials and Architecture, 2*(2), 132–144. <https://doi.org/10.17410/tema.v2i2.114>
- Rrapaj, I. (2018). *Le capriate lignee dell'architettura religiosa bolognese. Contributo della modellazione parametrica nell'interpretazione degli stati deformativi*. (Master's Degree Thesis). Alma Mater Studiorum - University of Bologna, Bologna.
- Scene 7.1 User's Manual. (2017). Faro Technologies.

Tampone, G. (1996). *Il restauro delle strutture di legno: il legname da costruzione, le strutture lignee e il loro studio, restauro, tecniche di esecuzione del restauro*. Milano: U. Hoepli.

Valeriani, S. (2006). *Kirchendächer in Rom: Beiträge zu Zimmermannskunst und Kirchenbau von der Spätantike bis zur Barockzeit = Capriate ecclesiae*. Petersberg: Imhof.

Venturino, A. (Ed.). (2015). *La Basilica di San Domenico in Bologna*. Bologna: ESD.

Zamperini, E. (2013). The Study of Timber Structures Based on In Situ Investigation. *Advanced Materials Research*, 778, 97–104. <https://doi.org/10.4028/www.scientific.net/AMR.778.97>

Zamperini, E. (2015). Timber trusses in Italy: the progressive prevailing of open-joint over closed-joint trusses. In *Fifth International Construction History Congress* (Vol. 3, pp. 629–639). Chicago: Construction History Society of America.