Luca Guardigli
Giovanni Mochi
Davide Prati

14

Knowledge Methods to Extend the Service Life of Historic Timber Roofs

KEYWORDS: CONSTRUCTION HISTORY AND PRESERVATION; TERRESTRIAL LASER SCANNING; PARAMETRIC MODELING AND RECONSTRUCTION; TIMBER HYGROSCOPIC AND RHEOLOGICAL BEHAVIOR; SERVICE LIFE

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 outline a methodological approach for an in-depth assessment of historic timber roofs, in order to extend their service life. In a holistic conception, digital technologies collaborate to identify mechanical, rheological and hygroscopic phenomena on wood elements over time, highlighting displacements, deformations and, generally, decay. Some case studies analyzed in the territory of Bologna were a useful starting point to achieve a thorough understanding of these artifacts, primarily based on survey, digital modeling and structural analysis. This academic approach, based on generative algorithms, is useful to attempt a more in-depth and transversal understanding of the behavior of these wooden structures, focusing on geometric surveying and constructive analysis. Developing and following a methodology accelerates modeling procedures and brings on new tools for analyzing these structural systems surveyed through Terrestrial Laser Scanning (TLS) devices. It also enables to store acquired results in BIM models in order to perform further analyses over time. The acquired knowledge of the structural behavior of timber structures is fundamental for their maintenance and for potential renovation.

INTRODUCTION

The analysis of historic roofing structures, in particular timber trusses, is present in many scientific contributions in the fields of building science and construction technology. Nevertheless, only a few studies have deeply investigated the behavior of these construction systems in a life cycle perspective, on the basis of detailed survey. This is justified by various factors, including that roofing structures are usually hidden and don't attract the attention of architects and engineers, except in case of severe damage, with imminent consequences on people's safety. However, the roof is a part of the building that is particularly subject to deterioration and fire, being characterized by strong modifications and partial replacements over time. To a certain extent, the service life of a roof determines the service life of the entire building.

One of the main reasons for the lack of attention lies in the fact that wooden roofs are typically indeterminate structures, whose safety depends mostly on the reliability of the original scheme, on the quality of wood and on the condition 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. Understanding the geometry, the structural behavior and the decay of wood is the key factor to extend the service life of a timber structure: partial replacements of parts can be part of the maintenance strategy.

The method proposed here for the assessment of timber trusses is compatible with the standard procedures and it is based on an accurate geometric survey of the structural parts of the roof. Following the survey, it is possible to go back to the original geometry of the structure through the rational use of reverse engineering software. Furthermore, counting on the development of detailed geometric models, it is possible to perform precise analyses on the rheological and hygroscopic behavior of the structures during their life cycle. All the information can be stored and confronted in a BIM model.

Figure 1: The roof of San Petronio, Bologna.

THE KNOWLEDGE OF HISTORIC TIMBER ROOFS AND TRUSSES

In construction history timber trusses are the main structures of timber roofs. They are commonly used to cover big halls and, particularly, the naves of the churches. These types of structures are conceived both as planar and tri-dimensional systems and realized with girders of solid wood of different sections, depending on the roof span. The ability to redistribute the vertical load without producing horizontal thrust on lateral walls gave success to these structural configurations since the beginning of the IV century.

Before the use of scientific methods, the architects used to solve the problem of building durable roofing systems following the advice of master builders and carpenters for their ability to produce and assemble reliable structural elements. Example of noteworthy trusses are represented by many architects in famous manuals, starting from the XV century (Philibert Delorme, Leonardo da Vinci, Taccola, G.B da Sangallo), but construction mostly depended on practice. In a well-known table by Sebastiano Serlio, titled armamenti di legname, the architect states that «the timber master will know how to manage it according to the place, therefore he won 't give any measures other than those in the drawings». These words clearly leave the selection of the beam sections and the solution of the details to the carpenters. The same statement can be applied to the maintenance of the roofs over time: the elements were continuously monitored and eventually replaced with new members, according to the evaluation of timber experts, not necessarily architects.

It is difficult to say how much roof construction in Europe derived from local culture, and how much the carpenters were travelling, spreading their knowledge in different regions. The construction and maintenance of trusses have certainly followed the culture of place, strongly depending on functional needs and materials supply. In Central Italy only, some species of wood were available, usually hardwood (chestnut, walnut, poplar, oak, pine). If the carpenters needed soft wood (fir) to build slender elements, they didn't hesitate to import the material from the Alpine region. We had evidence of that form historic documents in Bologna.

Southern European trusses are usually heavy structures, made with hard wood, while Northern European structures tend to be light structures. Heavy timber trusses are quite simple in form, and composed by a few elements. There are two basic systems: the system with a king post between the rafters, with or without braces (capriata semplice o all'italiana) and the system with a collar beam and queen posts (capriata palladiana). The scheme was the same for most of the trusses, up to a span of 15 meters. Beyond that dimension, it is usual to observe additional elements. (Fig.01)

A key issue in trusses construction is the function of the king post and its relation to the tie-beam. Some authors call "false truss" or truss-beam (falsa capriata, capriata trave) a truss where the king post rests on the tie-beam (pseudo-catena) and the rafters (falsi puntoni) on the king post. A similar distinction is made between open joint trusses and closed joint trusses. In open joint trusses (capriata a nodo aperto) the joint between the king post and the tie-beam is made through a not nailed steel bracket with the aim of simply maintaining the planarity of the structure, and avoiding the loads transfer; in the closed joint truss (capriata a nodo chiuso) the king post is placed on top of the tie-beam or clearly jointed (hinged), generating some bending moment in the element. (Fig.02)

The illustrations of the Traité theorique et pratique de l'Art de Batir by Rondelet (Planches from CIII to CXII) try to give an interpretation of the text of Vitruvius and show truss-beams and closed joint trusses. In Central Italy (Tuscany, Lazio, with the cities of Florence and Rome) the king post is frequently detached from the tie-beam, while in Northern Italy (Veneto, Lombardia with the cities of Milan and Venice), and in other parts Europe, as well as in most Architectural Treaties, it is linked to the tie-beam. In fact, Palladio, who was actively working in the Veneto region, describes and draws closed joint trusses:

Figure 2: Detail of bracket and wedges of a tie-beam in San Pietro, Bologna.

> There are various manners of disposing the timber of the roofs; but when the middle walls support the beams, they are very easily accomodated; which method pleaseth me very much, because the outwalls do not bear: so much weight, and altho' the head of some beam should rot, the roof is not withstanding in no danger

Similarly, in his drawings Philibert Delorme identifies closed joints (bolted joints). Until the XVI century the Italian experience was very influential in the work of European architects. In their structural conception Northern European trusses tend to become lighter and more complex over time.

While the knowledge of wide span wooden roofing, in particular timber trusses, is based on the analysis of old textbooks, the interpretation of the mechanical behavior usually follows the XIX century approach, simplifying complex and partly structurally indeterminate systems into manageable and computable truss diagrams. The technical solutions identified for strengthening or preservation are often based on those simplifying assumptions.

Our assumption is that digital technologies for surveying enable a series of new and original considerations that would be almost unworkable following the traditional methods based on direct observations and simplified architectural surveys.

While the use of the laser scanner in the survey of old buildings is quite widespread, less frequent, if not absent, is the application of this technology to hidden spatial structures as timber roofs. Studies in this direction, at least in Italy, are very few. The starting hypothesis is to take advantage of the large amount of geometric data acquired in form of point clouds, in order to analyze the trusses in detail and derive accurate information on their behavior. The acquisition of further information allows to trace the logic of construction and, above all, the process of assembly of the structures from the very beginning. In fact, the geometry of the trusses follows a very precise, and often ignored, construction process linked to the possibility of raising the elements up to the base of the roof, refining and assembling them through other supporting elements and, finally, joining them using metal nails. Nowadays, the system for joining wooden elements is completely changed with the introduction of metal plates and the possibility to check every part of the system numerically; as a matter of fact, retracing the original logic of the junctions is a non-trivial task. Besides, extensive and detailed geometric information provide highly interesting data on deformations and displacements. These modifications in shape occur both at local level, i.e. in a single element, and at global level, considering the behavior of the whole roofing system. Traditionally, roof systems have been studied in two dimensions. The global behavior, provided by movements and reciprocal interferences in the longitudinal direction, has often been ignored in favor of the behavior of the single truss in its virtual plane.

A further consideration concerns the intervention on this type of structures: a poor understanding of the original construction leads to interventions that bring back the behavior of trusses to simplified schemes, introducing stiffeners and other superfluous structures that are radically changing the original behavior of the structure. Recent major refurbishment interventions in Bologna, as we have observed, have shown a deep misunderstanding of the structural behavior, both locally and globally. Not to mention the adoption of extended replacements of elements that have created problems not only to the roof system, but also to the whole building.

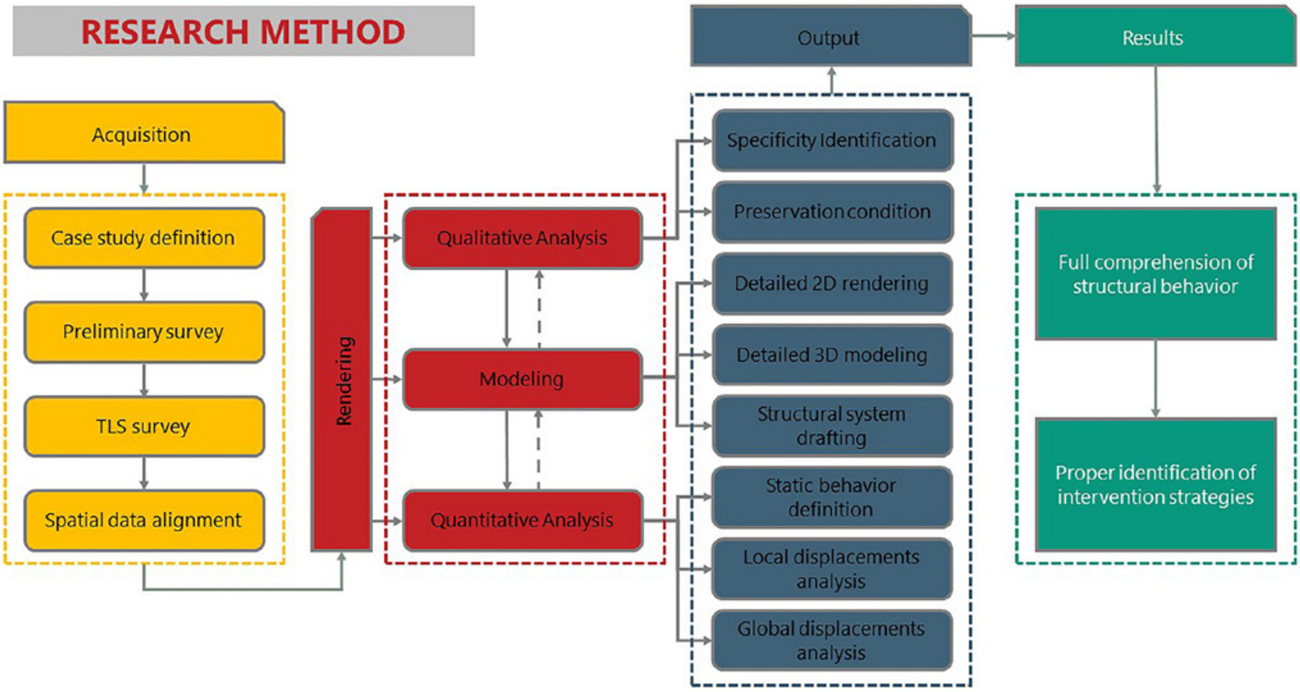
LIFE CYCLE OF HISTORIC TIMBER ROOFS

The life cycle of a timber structure can be very long; in many churches of Bologna the same structures have been used for more than 400 hundred years. In some case many parts of the trusses were replaced; in other occasions the elements were disassembled and then re-assembled. If they were found excessively deformed or damaged by humidity or animals, they were cut, shortened, turned upside down and eventually replaced.

The maintenance of any historic roof of particular importance (palazzos, churches, theatres) has always been essential over the years to ensure a very long lifecycle: interventions were continuous and represented one of the main running costs of the building, before the services were introduced and the energy consumption became a major issue. The good functioning of the building mainly depended on the good care of the roof elements.

Usually the decay of historic roofs roughly depends on two main factors: the leakage from the coat of the roof and the dysfunctions of the main structure, due to major displacements or material damage. Maintenance planning always depended on the recognition of the damage, following more or less detailed visual inspections.

Today the leakage of historic roofs is often resolved with the introduction of waterproofing membranes; these membranes have increased the weight of the roof and reduced the transpiration of the roof, but have substantially guaranteed a complete waterproofing and protection, in such a way that well-preserved historic roofs are now more durable than the past, not having the necessity of ensuring waterproofing through discontinuous elements like tiles. Nevertheless, one problem of the roof is still the collapse of the original small sealing bricks or stucco pieces onto the space underneath, especially with the absence of false ceilings, which have a protection role until a certain point; the fall of small elements, even if restricted to little areas, can be extremely dangerous in rooms and halls occupied



by a large number of visitors. This safety aspect that in the past was tolerated, nowadays is not accepted. For this reason, any little fall must be avoided with frequent inspections of the roof.

THE SURVEY PROCEDURE

For the assessment of the roof, a survey procedure has been set up, tested and developed by subsequent approximations in different case studies. The case studies are represented by a set of important churches in Bologna, all built between the 16th and 18th centuries, whose pitched roofs are supported by timber trusses. The most interesting structures belong to the Cathedral of San Pietro, the church of San Salvatore Maggiore, the church of San Giovanni in Monte, the Basilica of San Petronio and the Basilica of San Domenico. These buildings are built in the same period and some of their naves have unusually big dimensions the trusses of San Pietro were possibly the biggest in Italy – and perhaps in Europe – at the time of construction.
The procedure should follow a preliminary visual and technological survey of the roof but in some occasions, it is the only way of carrying out the preliminary analysis if the structures are not safely accessible. The procedure can be graphically summarized in a synoptic diagram that represents different steps. The method takes advantage of the feedback from the case studies, but can be easily adapted to different contexts. (Fig.03)
The first step is data acquisition, followed by a rendering phase, which provides many outputs (photos, drawings, diagrams and models) which represent the operative tool for the interpretation of the behavior of the studied building. The interpretation of the results allows to depict coherent structural configurations, disengaging them, where necessary, from usual and standardized techniques.
The method has been developed through its application in different case studies, in which 3D surveying instruments and reverse engineering techniques have been used. Reverse engineering is the detailed analysis of a real object aimed at producing or modeling a new object with similar characteristics. Starting from a prototype, or an object that needs to be reproduced, the process of reverse engineering has the goal to derive reference vectorized models. The models are used to carry out dimensional analyses, replace existing parts, and eventually develop completely new parts with improved efficiency.
In the acquisition phase the object of interest needs to be first identified. Depending on the equipment, a preparatory inspection is essential to plan the phases of survey properly and become familiar with these spaces which are often difficult to access. Once the inspection has verified the feasibility of the survey, the scan session is carried out using a laser scanner. For the churches we used the scanner FARO CAM2 FOCUS 3D. This

Figure 3: Synoptic diagram of the procedure: data acquisition phase through laser scanner (yellow), rendering and analysis of the point cloud data (red), output (blue) and achieved results (green).

lightweight and easy to use instrument provides fast scans with an acceptable precision. In fact, the possibility of using a targetless technique minimizes the preparatory activities and the dead time between each scan station. The conclusion of the survey is followed by the phase of spatial data consolidation, performed in back office: the stations are aligned to generate point clouds, a true metric dimensional information repository of the detected object, to which documentary and photographic information can be associated. The consolidated dataset helps to ensure the traceability of data.

The rendering phase leads to three different actions, that are independent but logically consequential: the qualitative analysis, the digital modeling and the quantitative analysis. Each of the three stages is associated with specific outputs (blue boxes in figure). The information related to these outputs can be stored independently or managed into a BIM model.

The qualitative analysis involves the careful observation and understanding of the acquired data, and shifts all considerations to back office. The digitized spatial data are always completely available and it is not necessary to come back to the survey site to retrieve forgotten information. This analysis allows to identify the specific nature and complexity of the roof under investigation, avoiding what might be called reductio ad unum, that is the representation of a single parts according to simplified schemes, whereas there might be slight but significant differences within the same roofing system. Through the direct observation and the extraction of orthophotos from the point cloud an abacus and an overall picture of all the nodes of the different trusses can be drawn up.

Some considerations can also be made on the state of conservation of the structures, identifying the areas where other tests should be made with non-destructive methods, in addition to laser scanning: identification of wood species, determination of wood moisture content values and moisture gradients, determination of strength grade or strength values to be used in the structural analyses, characterization of biological damage.

The digital modeling phase follows the first qualitative assessment of the roof and gives a very detailed representation of the object of the survey: 2D drawings can be traced through operations of vectorization of the orthophotos and the amount of spatial data collected is useful to create 3D models. It is possible to transform the point cloud into 3D models of all trusses using parametric modeling tools with generative algorithms.

After extracting from the project point cloud only the portion representing the truss object of study, some clipping boxes are created in strategic positions close to the knots. Size and orientation of the boxes vary according to the sectioned elements, remaining as orthogonal as possible to each section. These cross sections are exported in the 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 by keeping fixed the reference system of the global point cloud. After having exported the cross sections, their vectorization is performed automatically using built-in vectorization tools. This is possible because of the extreme simplicity of each cross section and

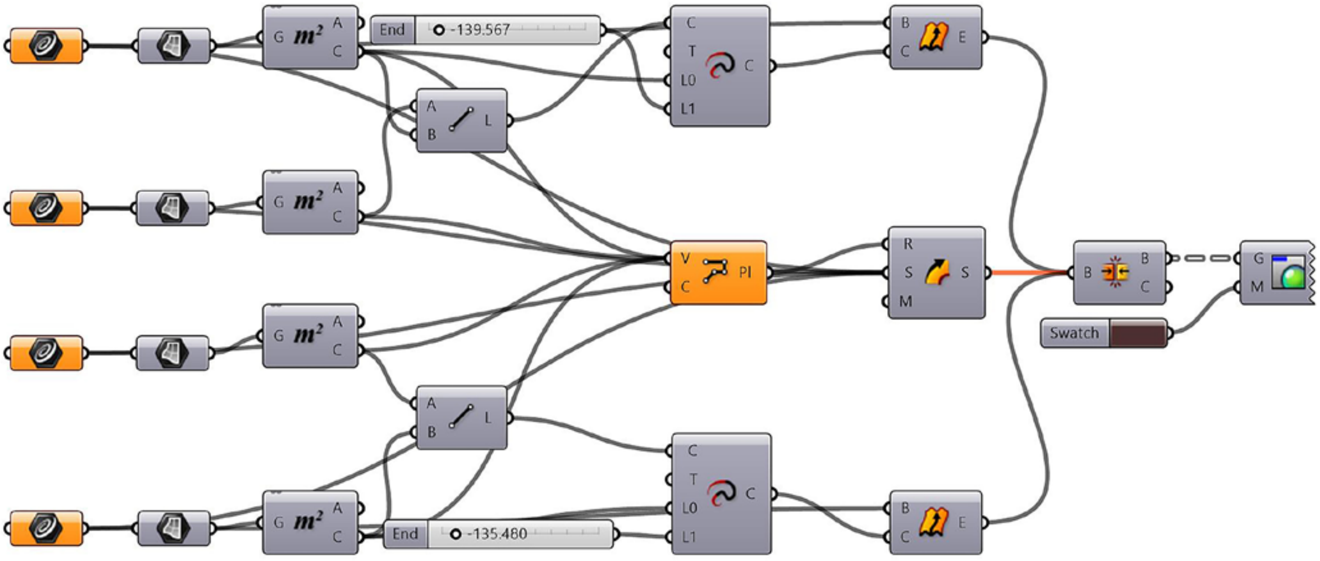
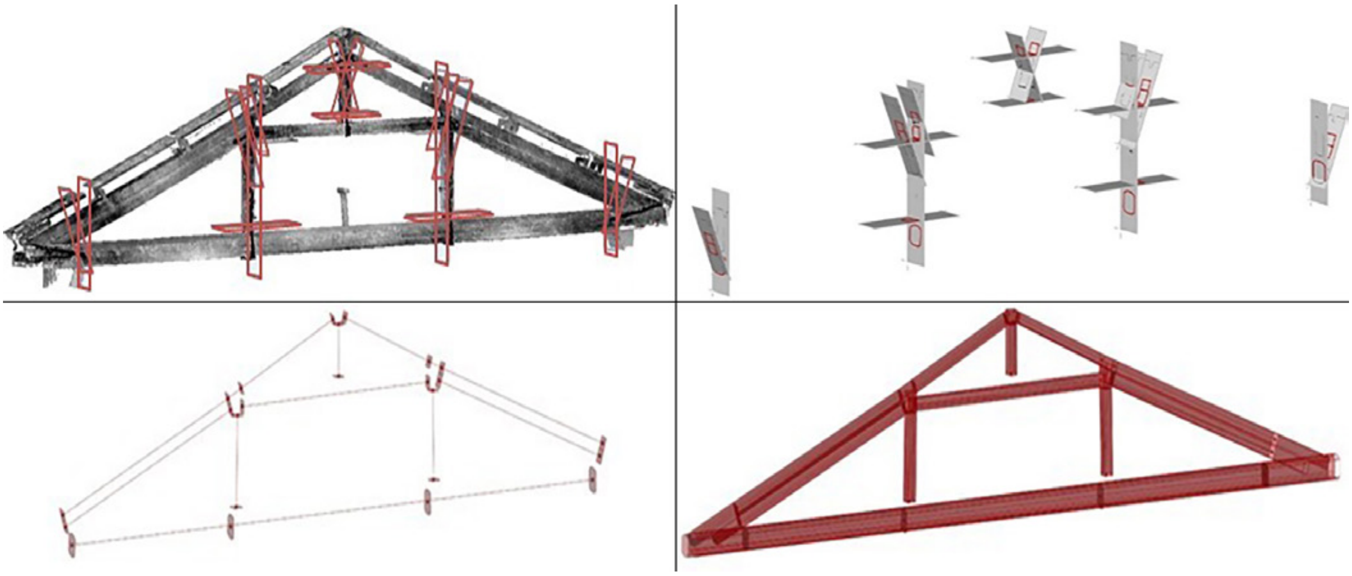


Figure 4: Modelling process of a truss element created with Grasshopper generative algorithms. Each box represents an operation with an input on its left and output on its right. The connections between the boxes indicate the order of the operations. By connecting the outputs of an operation to the inputs of another operation, the result model is automatically generated and it depends on the initial parameters set manually.



the limited number of points. Automatic vectorization or meshing of the entire truss always lead to incongruous models. Therefore, the process of model generation is defined using the Rhinoceros 3D plugin Grasshopper. First of all, the previously obtained section curves are implemented as input parameters. This means that the final output of the entire algorithm depends exclusively on the inserted curves. (Fig.04)

Each box of figure 05, which represents the queen post of the truss of S. Domenico in Bologna, corresponds to one operation. Starting from upper left, the boxes represent the section curves that are the input parameters. Then the algorithm transforms the implemented curves into surfaces (upper right). Once identified surfaces surrounded by input curves, the algorithm calculates their area and the center of gravity and then traces a polyline joining the newly identified centers of gravity (left below). Finally, the algorithm extrudes the sections along the axes defined by the centers of gravity (right below), thus obtaining the 3D profile of each beam. To create knots, section curves are extended along their 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. (Fig.05)

Number and position of the sections used is decided in order to have the best-fitted 3D model with the lowest number of sections. The creation of clipping boxes and orthophotos and the subsequent vectorization represent the most time-consuming steps of the whole method. Using only a few sections strongly affects the speed of the proposed method.

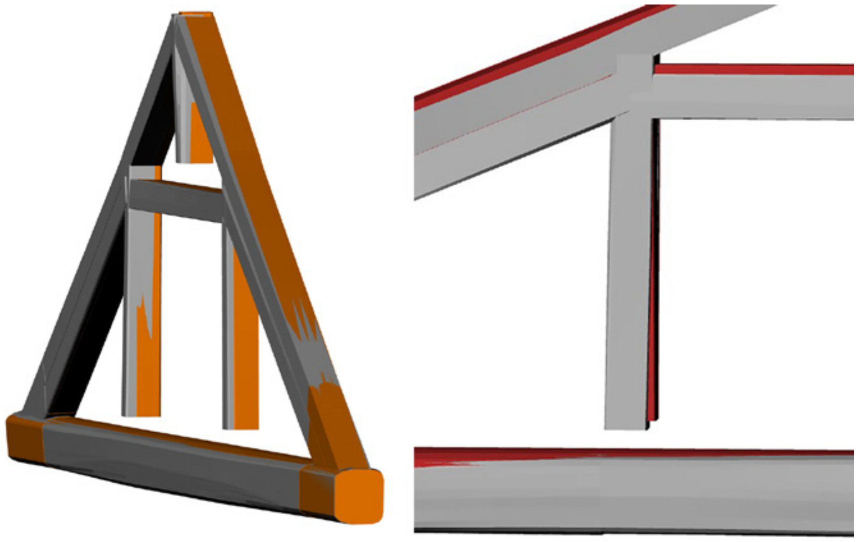
The precise wireframe models can be provided to analyze the behavior of the structures with a finite element calculation software. Furthermore, using reverse engineering software it is possible to compare 3D models with the original point cloud in order to highlight displacements and deformation in every element of the truss.

In fact, the spatial data can be used to create inferred 3D models through a simplified rectification of the rods and the identification of an “ideal truss”. This ideal 3D model is the one that best represents the initial, undeformed condition, and can be used as a BIM model to provide a basis for systematic knowledge that is traceable, objective, comparable and available at any time. This operational method is not linked to any standardization and can consider the specificities of each construction. Subsequently, it is possible to make targeted suggestions for maintenance strategies in order to extend timber trusses service life. Outputs can be considered also as a new starting point for the roofing from which to monitor its behavior over time. This approach favors even the sustainability of maintenance in terms of reversibility, compatibility and proper use of current techniques.

The ideal 3D model is conceived with the aim of 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 has to be made in order to proceed with the construction of this model. The basic principle is to bring the basic 3D model, to a pre-condition without displacements and deformations. In other words, to what it is supposed to be the original condition at the time of construction.

First of all, all members forming the truss are brought into a single perfectly

Figure 5: : a) The red rectangles indicate the clipping boxes used for the sectioning of the cloud. b) Traces of the sections obtained directly from portioned point cloud are highlighted in red. c) Surfaces created by the algorithm from the previously obtained sections and their connection through each section’s barycenter. d) Result of the modelling process.



vertical plane passing through both the supports of the tie beam. This decision is justified by the fact that supports of the tie beam on the masonry walls are comparable to fixed points. Therefore, it is assumed that the displacements occurred in correspondence of the supports 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 having identified the ideal vertical plane, passing through both the supports of the truss, all the centers of gravity of the vectorized sections are projected into this plane. In this way, a perfectly planar structure is modeled, which highlights the occurred displacements from the plane itself. Figure 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.

Next, the rectification of each truss member is carried out. The main purpose of this step is to highlight further deformations and displacements not identified by previous steps, especially due to bending moment. This process is performed using Grasshopper algorithms. First, the modeling of each member is made with only two vectorized extremity sections to obtain straight elements. In order to rectify all the edges, the members have been rotated as to reach mutual orthogonality. This step is carried out aligning the center of gravity of the vectorized sections at the free extremity of the member, with the straight perpendicular line passing through the center of mass of the vectorized section at the fixed end of the same member. Figure 06 shows how this operation puts in evidence the members of the rectified 3D model compared to those of the basic 3D model, highlighting the rotations occurred.

After having been rendered, the detailed 3D models of the current geometry of each truss and the detailed ideal 3D models of the undeformed original situation are overlapped to highlight the dimensional differences. This step is carried out using the reverse engineering software Geomagic Control

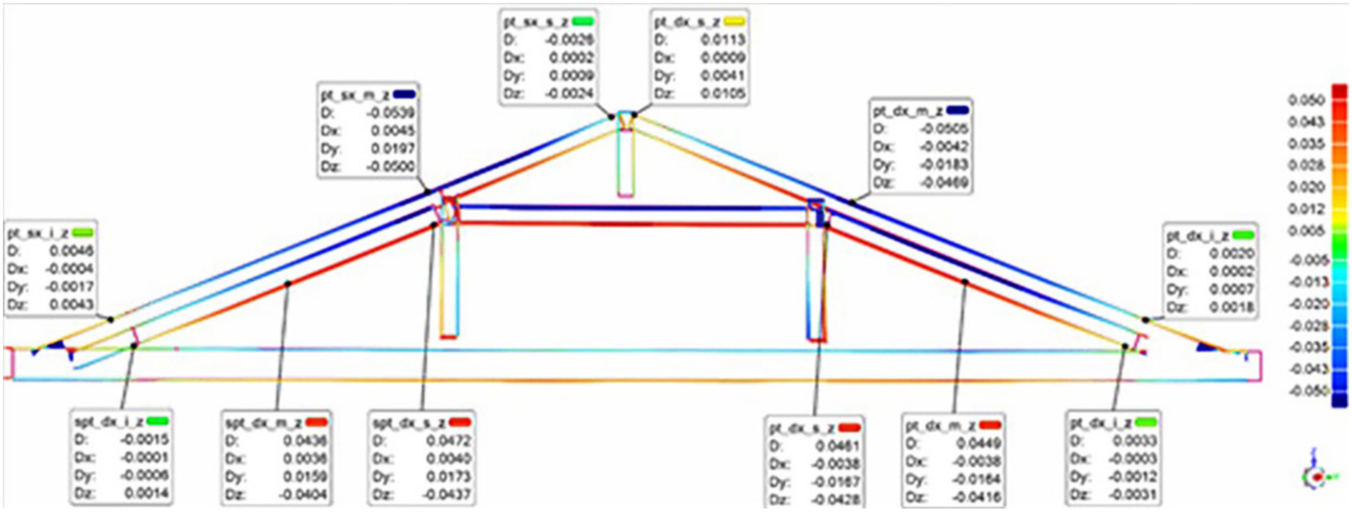
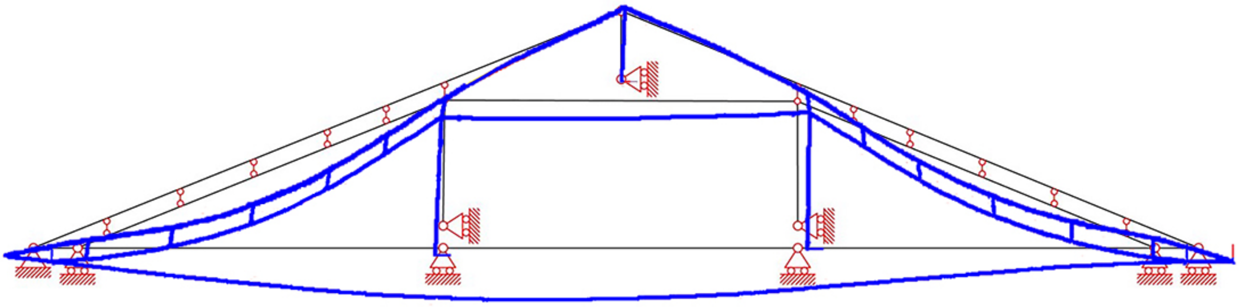


Figure 6: a) Highlighting of the displacements of the truss by overlapping the base model represented in grey with the one obtained from the projection of the sections to the trusses' perfectly vertical plane represented in orange. b) Highlighting the deformations by overlapping the base model represented in grey with the one obtained from the projected and linearized elements represented in red.

Figure 7: Detailed and theoretical model overlapped: 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 interval between 5 and 7 cm.



that is able to examine and graphically report, in chromatic scale, the deviation between every corresponding points of the 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.

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 the displacements and deformations life of each truss. All movements and deformations that each truss underwent over time in the entire roofing.

Moreover, lowering 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 withstand by the whole roofing.

Comparisons can be made between two complete 3D models, 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 representation, a precise quantification them 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.07)

An aspect that is considered in the structural analysis is the long-term dimensional deformation due to hygroscopic phenomena. The viscosity of the timber trusses must be taken into high consideration, because it is responsible of creep and potential failure of the structure over the long period. The deformation due to viscosity is detected through the above-mentioned operations, starting from the geometry of the "ideal truss".

The shrinkage coefficient due to humidity under the saturation point is expressed by the formula:

$$\varepsilon_{LRT} = \frac{\Delta L_{LRT}}{L_{LRT} \times \Delta\mu} \times 100$$

where Dμ is the time-dependent variation of moisture in wood. Applying the effect of moisture in the FEM model of the truss, it is possible to make a confrontation between the ideal geometry and the actual configuration, evaluating the long-term deformation due to mechanical loads, temperature and humidity. (Fig.08)

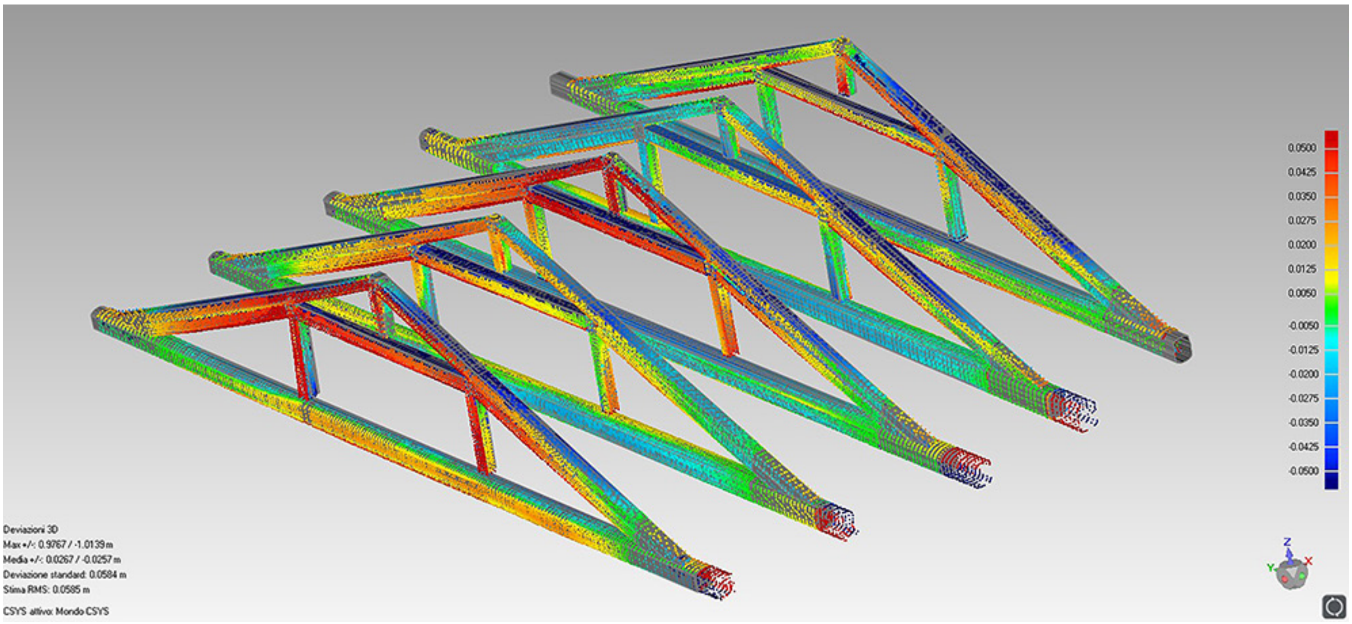
DISCUSSION

One possible future development regards the refinement and the simplification of the whole procedure; for instance, the creation of the BIM model is still under implementation. (Fig.09)

The final goal of the procedure would be to operate the comparison between deformations in the Rhino model and the deformations in the structural model in a BIM environment.

Exporting static geometries is working fine from Rhino but when it comes to a BIM workflow simply exporting is not enough. Static geometries won't intersect with native elements and are difficult to enhance with parameters. Redrawing geometry with native BIM elements often seems to be the only solution. But then, any design change is forcing you to repeat. Open source software like Grevit or GeometryGym creates BIM elements from Rhino and also allows the designer to update BIM elements later according to latest design changes while all parameter values remain in place. A designer working in Grasshopper can send their geometries to one Revit instance. In fact, it is possible to use curves scripted in Grasshopper to create numerous native BIM elements inside BIM software (Fig.10). The aim is to generate a federated BIM model using computational BIM workflows starting from Rhino/GH. With the tightly coupled approach, systems are coupled through the Application Programming Interface

Figure 8: Deformations in the structural model.



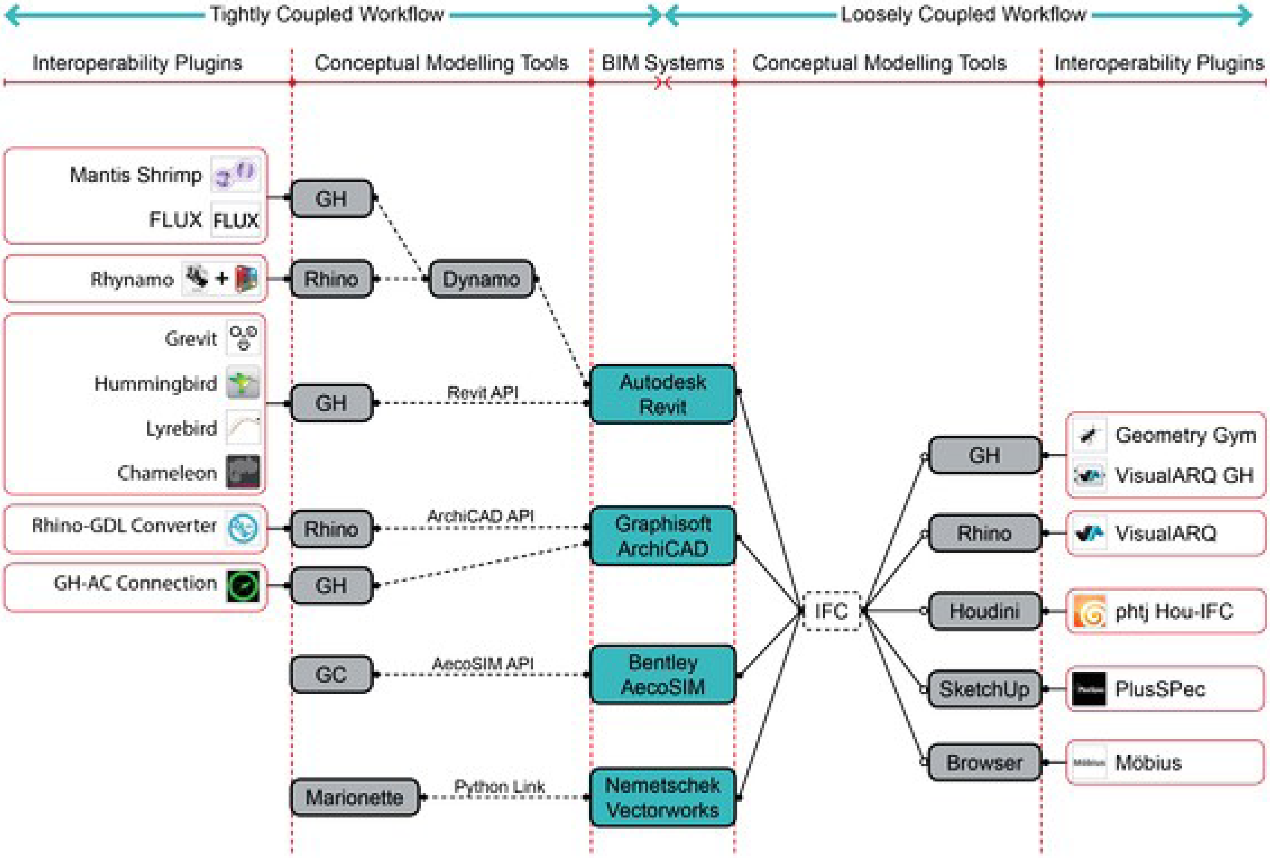


Figure 9: 3D model to be translated into a BIM model.
Figure 10: Computational BIM workflows that are in use today.

(API) provided by the BIM system. In this case, graph-based systems communicate via the API of the BIM system, directly instantiating geometry in the BIM model each time the graph-based model is executed. With the Loosely Coupled approach, systems are coupled through model exchange. The graph-based system typically generates data in a standard file format that can be directly imported into the BIM system. (Fig.10)

CONCLUSIONS

The geometrical results have led to a better comprehension of the displacements and the deformations of the elements. In most of the cases the results of the structural models were confirming these long-term deformations due to moisture; in general terms it was possible to detect the general shrinkage and relaxation of the structural systems over time. For instance, many brackets of the king posts were not able to perform the original task of supporting the tie beams. In some and active systems were conceived to stop or, at least, slow down this natural process of viscous deformation. In a few cases rotations of the joints and the elements were detected: in these conditions the necessity of replacing weak or displaced elements or reinforce the joints was reported. The method that has been defined will be implemented into a BIM software to be used for the life cycle planning of the roof structures. In fact, it is possible to repeat the same analysis after a few years, detecting the variations. With this procedure it is possible to monitor in time the deformation of the roof, selecting deformation that cannot be seen in a global vision; while in the past deformation could be observed locally, in such a way it is possible to detain displacements in a whole perspective, locating the tendency of the roof, and, especially, the speed of the deformation over time; confronting two models in a reliable space of time, like 7-10 years for instance under normal conditions, it is possible to detect different positions. In such a way the maintenance costs can be better evaluated. It is obvious that this deep analysis should not substitute a material and local survey.

Bibliografia
Bibliography

Barbisan, Umberto, e Franco Laner. *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, 2000.

Bertolini, Clara, Stefano Invernizzi, Tanja Marzi, e Antonia Teresa Spano'. *Numerical Survey, Analysis and Assessment of Past Interventions on Historical Timber Structures: The Roof of Valentino Castle*, 2:581–92. Dolnośląskie Wydawnictwo Edukacyjne, 2015. https://iris.polito.it/handle/11583/2616930#.W8i21mgzaHs.

Cruz, Helena, David Yeomans, Eleftheria Tsakanika, Nicola Macchioni, Andre Jorissen, Manuel Touza, Massimo Mannucci, e Paulo B. Lourenço. *Guidelines for On-Site Assessment of Historic Timber Structures.* International Journal of Architectural Heritage 9, n. 3 (3 April 2015): 277–89. https://doi.org/10.1080/15583058.2013.774070.

Holzer, Siegfried M., Joseph R. Loferski, e David A. Dillard. *A Review Of Creep In Wood: Concepts Relevant To Develop Long-Term Behavior Predictions For Wood Structures*. Wood and Fiber Science 21, n. 4 (22 June 2007): 376–92.

Luigi, Ponza Di San Martino. *Istituzioni di architettura civile*. Istituzioni di architettura civile, 1836.

Munafò, Placido. *Le capriate lignee antiche per i tetti a bassa pendenza: evoluzione, dissesti, tecniche di intervento*. Firenze: Alinea, 2002.

Prati, Davide, Giovanni Mochi, e Luca Guardigli. *Contribution to the Knowledge of Wide Span Wooden Roofing in the Area of Bologna*. Tema: Technology, Engineering, Materials and Architecture 2, n. 2 (21 December 2016): 132–44. https://doi.org/10.17410/tema.v2i2.114
.
Prati, Davide, Ildeina Rrapaj, e Giovanni Mochi. *Contribution of Parametric Modeling in the Interpretation of Deformations and Displacements of Wooden Trusses*. SCIRES-IT - SCIentific RESearch and Information Technology 8, n. 1 (11 July 2018): 105–20. https://doi.org/10.2423/i22394303v8n1p105.

Rondelet, Jean Baptiste. *Traité théorique et pratique de l'art de bâtir.* Paris: Chez l'auteur, 1812. http://archive.org/details/traitetheoriquee05rond.

UNI 11138:2004. *Beni culturali - Manufatti lignei - Strutture portanti degli edifici - Criteri per la valutazione preventiva, la progettazione e l'esecuzione di interventi*, 2004.

UNI 11161:2005. *Beni culturali - Manufatti lignei - Linee guida per la conservazione, il restauro e la manutenzione*, 2005.

Why Do Architects Need Computational BIM Workflows? – WOWAD. WOW Architecture + Design. Retrieved from: https://wowad.in/why-do-we-need-computational-bim-workflows/.

Yeomans, David T. *The Development of Timber as a Structural Material*. Routledge, 2017.

Zamperini, Emanuele. *Timber trusses in Italy: the progressive prevailing of open-joint over closed-joint trusses*. In Fifth International Construction History Congress, 3:629–39. Chicago: Construction History Society of America, 2015.