POLITECNICO DI MILANO

Master in

Building Information Modelling

European Master in
Building Information Modelling

Historic Building Information Modelling (HBIM) from points clouds to the modelling of complex geometrical elements and thematic information

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Co-funded by the
Erasmus+ Programme
of the European Union

a.a. 2021/2022

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ACKNOWLEDGEMENTS

I would like to express my gratitude to all of our professors in the BIM A plus programme for their time and effort to bring us to this moment. Many thanks to the European Union for establishing the Erasmus Mundus Programme and for granting me a full scholarship for this programme.

I wish also to extend my special thanks to Prof. Daniela Oreni, and prof. Pietro Crespi, my primary supervisors, for their mentorship throughout this thesis. I would also like to express my deep appreciation to my Master's classmates who encouraged me and provided valuable insight into my research, especially those from "Ruggero Leoncavallo 17". I would like to thank my parents and siblings for supporting me through the hardships, believing in me and encouraging me on my journey to success.

To the soul of Ahmed Moshtohry …

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

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SOMMARIO

L'Heritage Building Information Modelling (HBIM) è un flusso di lavoro che si concentra sulla creazione di file proprietari tridimensionali a partire da dati fisici come scansioni laser, nuvola di punti o rilievi fotografici, nonché dalle informazioni e dai riferimenti storici rinvenuti negli archivi pubblici e privati. Questi file possono essere utilizzati per diversi scopi. Di conseguenza, gli oggetti parametrici, ricchi di informazioni e di classi, possono essere utilizzati nel processo di gestione degli asset fino alle fasi di conservazione, riparazione e manutenzione (CRM) della struttura del patrimonio edilizio. Tuttavia, le informazioni devono essere anzitutto raccolte e successivamente immagazzinate in un unico contenitore per poter essere manipolate e mappare le corrispondenti categorie geometriche con quelle dell'edificio. In questo modo è possibile ottenere una libreria completa di oggetti che possono essere utilizzati per analizzare i carichi, riprogettare le sezioni, riparare, eseguire interventi, mantenere e gestire la struttura. A causa della limitata comprensione del caso studio in oggetto, la "Chiesa di San Giacomo", e della sua funzione primaria, ci sono state delle difficoltà nell'acquisire testimonianze storiche. Questa è stata una delle ragioni per cui è stato così impegnativo. Tuttavia, siamo riusciti ad acquisire le informazioni necessarie per l'indagine e a documentare i componenti del tetto per lo studio, che era il nostro obiettivo principale. I dettagli del modello sono stati realizzati utilizzando le stesse tecniche di costruzione e lavorazione del legno applicate durante la creazione del modello originale. L'utilizzo di una software BIM (Building Information Modelling) come Revit è stato incredibilmente vantaggioso nel processo di sviluppo delle famiglie parametriche, che in ultima analisi ha portato a un processo di modellazione più semplice. A ciò si aggiunge l'ampia libreria di materiali del software, che consente di assegnare a qualsiasi oggetto il materiale più appropriato. Il prodotto finale sarà un modello HBIM 3D dettagliato del tetto della chiesa, completo di caratteristiche degli oggetti nascosti oltre la superficie scansionata, nonché di dimensioni, materiali e dati di costruzione. Questo modello sarà creato utilizzando Revit. Il modello completato è in grado di generare sezioni trasversali, dettagli e planimetrie, oltre a un modello 3D analitico per lo studio strutturale, necessario per garantire la sicurezza della struttura e sviluppare un piano di manutenzione per la conservazione dell'edificio storico.

Parole chiave: (Architettura, HBIM, Modellazione, Nuvola di punti, Patrimonio Storico)

ABSTRACT

Heritage Building Information Modelling (HBIM) is a workflow that focuses on the creation of three-dimensional (3D) proprietary files from physical data such as point cloud laser scans or image surveys, as well as historical architectural data discovered in building archives and historical references. These files can be used for a variety of purposes. As a consequence of this, parametric objects that are packed with information and classes can be utilised in the process of asset management all the way through the conservation, repair, and maintenance (CRM) stages of a heritage building structure. However, information must first be gathered and stored in a single reservoir in order to manipulate and map each geometric building category with its corresponding building category. This will result in a full library of objects that can be used to analyse loads, redesign sections, repair, apply interventions, maintain, and operate the structure. Due to a lack of understanding regarding the subject of this study, "Chiesa di San Giacomo," and its primary function, it was challenging to acquire historical evidence for this thesis. This was one of the reasons why it was so difficult. Nevertheless, we were successful in acquiring the information required for the investigation and in documenting the components of the roof of the study, which was our primary focus. The details of the model were crafted utilising the same building and woodworking techniques that were applied during the model's original creation. Utilizing BIM (Building Information Modelling) software like Revit was incredibly beneficial in the process of developing parametric families, which ultimately resulted in a simpler modelling process. This was in addition to the software's extensive material library, which provides the capability for any object to be allocated to the material that is most appropriate for it. The finished product will be a detailed 3D HBIM model of the roof of the church, replete with characteristics for the concealed items beyond the scanned surface, as well as dimensions, materials, and construction data. This model will be created using Revit. The completed model has the capability of generating cross-sections, details, and schedules, in addition to an analytical 3D model for structural study, which is necessary for ensuring the structure's safety and developing a maintenance plan for the preservation of the heritage building.

Keywords: (Architecture, HBIM, Heritage, Modelling, Point cloud)

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1. INTRODUCTION

The acronym "BIM" (which stands for "Building Information Modelling") has been variously defined by a large number of different scholars. Based on how the model is used, BIM can be considered one of the most effective digital workflows for managing projects. This is because the process collects information, creates 3D geometries, and stores the data throughout its lifecycle. The procedure maintains data on both newly developed assets and those already in existence. Building a digital asset that conforms to standards in terms of geometry, semantics, component classification, and properties is required in order to create a BIM database. This asset must be built before a BIM database can be created.

When it comes to existing buildings, the amount of information that is often stored is substantial, but this number might vary widely due to the considerable research that was done on the building and the numerous information sources. A data storage facility capable of holding this much information and cutting-edge software are both necessities for effective management of such a large volume of data (Bonduel, et al., 2021). In addition to that, prior to beginning the process of reverse engineering, it is necessary to determine the uses of the model. This is done in order to concentrate efforts in a smaller area and cut back on the total amount of work done. The information needs that need to be included in the 3D digital models are defined and organised based on how the models are going to be used (BIMe Initiative, 2019).

Heritage Building Information Modelling (HBIM) is an application of the BIM workflow. It is a method of integrating several types of data extracted from a point cloud, photogrammetry, images, and traditional surveys with historic data to represent constructed three-dimensional elements and map them with one another. The methods that are usually used combine cutting-edge technologies with old architectural manuscripts to generate data for parametric elements and to ensure that the same construction techniques from the same era are used (Murphy, et al., 2013). According to the standards established by the International Organization for Standardization (ISO 19650–1, 2018), the process of creating a digital representation of a built asset simplifies the design, construction, and operation processes while also providing a reliable digital source for decision-making.

The case study that we have in this thesis is the church of San Giacomo in Como, Italy. The church lacks a lot of information due to being very old. However, the dating process for the ancient church was largely based on comparing geometries with other buildings from the same era, and the same elements were also visible in other basilicas and abbeys. The only sources we had access to for the study were the "Regione Lombardia" website, site visits to the location, and old books on construction technologies for similar buildings in similar ancient times. The use of the historical information offered by these sources enabled the creation of the building's details, and cross-software management was used to map the created library of parametric objects with the point cloud scans and the image survey data. The final product was a complete roof model over the nave, transepts, and apse, and it can be used to create longitudinal and local sections, thoroughly examine elements, and create 3D models from the Historic Building Information Model for load analysis and maintenance plans.

1.1. SWOT ANALYSIS FOR THE USE OF HBIM

The use of HBIM as a workflow to manage a heritage building requires a SWOT analysis to identify its suitability for the project. The SWOT analysis is a technique for assessing a process's strengths, weaknesses, opportunities, and threats. It is used to expand the scope of detected risks in risk identification by considering internally created risks. The technique identifies the process’s strengths and weaknesses, then the opportunities that can be produced from those strengths and the threats that can be generated based on those weaknesses. The analysis also figures out if process weaknesses could make it hard to take advantage of opportunities and how much organisational strengths could make up for threats (Project Management Institute, 2017). Figure 1 depicts a SWOT analysis derived from a similar study achieved in a doctoral thesis on the usage of BIM processes by Bruno et al. (2018). Similarly, HBIM shares the same items but with a greater emphasis on heritage.

Figure 1 – SOWT Analysis for the HBIM Process

1.1.1. Strength

The workflow will make it possible for the heritage to have a digital database, which will make it easier to manage the heritage as a facility for operation; to make use of its unique data on different levels (3D, 4D,.., nD); to archive the information generated and manipulate it through a common data environment (CDE) that can make it accessible to all of the appointed parties; to facilitate interoperability between restoration specialists; to maintain budgetary control; and to study the model digitally and physically (Nieto-Julián, et al., 2021).

1.1.2. Weakness

The HBIM process lacks building-specific information and is primarily based on antiquated references that are rarely available. It can also be inaccurate if the participating parties don't work together, and it also calls for cutting-edge technology and software customization to make it easier to manipulate data and create three-dimensional heritage models (Nieto-Julián, et al., 2021).

1.1.3. Opportunities

Many opportunities can be developed as a result of the strengths of the HBIM process. These strengths include the following: It can operate as a technique to control the procedures, which means that the preliminary findings are incorporated into the system to be optimised and maintained through the CDE, maximising the efficiency of the management process throughout the lifecycle of heritage buildings; Integration of data storage and retrieval systems via the model, participation of all of the actors through the application of the industry foundation classes (IFC) format to the heritage model (Nieto-Julián, et al., 2021). Machine learning and training to recognise geometries through the use of algorithms for locating point cloud leaser scans are both included (Ma, et al., 2020).

1.1.4. Threats

Finally, the threats that can be developed as a result of the weaknesses can be summed up in the huge amounts of data handled by the BIM model; the massive file sizes for the laser scan and photogrammetry; and the lack of information offered about the heritage building, which may or may not be available depending on the year of establishment and the documents available; cultural inadequacies and unwillingness to transition to new BIM technology and replace old ways of doing things; the lack of follow-up in terms of communication between engineering and non-engineering parties (Nieto-Julián, et al., 2021).

1.2. HISTORY OF THE PROBLEM AND SUBJECT OF RESEARCH

The roof of Como's San Giacomo church serves as the study's focal point. The cross vaults of the central nave are covered by a wooden truss roof that supports a layer of stone slates (Catalano, 2004). The trusses have warped significantly due to obsolete construction and environmental variables such as dampness, snow loads, and aged material. The church has previously been renovated twice. According to Bishop Ninguarda, the first intervention began in 1578 when severe decay was discovered and lasted twelve years. Then the building went through a lot of repairs and changes that made its original shapes look very different. The cross vaults in the central nave were built, the octagonal lantern from the dome was removed, the side apses were closed and converted into sacristies, and the floor level was raised. Columns were transformed into hefty pillars. At the same time, the development of private structures around the church developed, making it increasingly difficult to read the shapes, particularly in the apse (Catalano, 2004).

The second intervention occurred in the early 1870s when a restoration intervention was required because the lantern was in danger of falling, but it was also prompted by a recognition of the church's historical and architectural value. Thus, the lantern's original octagonal shape was restored, as were the eight tuff oculi and mullioned windows uncovered in its masonry. The trusses were restored, raising and bringing them back to their original inclination to restore the four huge arches at the foot of the lantern, through which one could see the trusses themselves. In addition, the northern arm of the transept's covering was reconstructed (Catalano, 2004).

According to the cathedral's constituent museum, the third intervention for restoration work on the church of San Giacomo will commence in 2022. The original materials will be preserved with the use of cutting-edge, non-invasive techniques. There are also proposals for art shows and archaeological explorations. The intervention is made possible by a bequest of 10 million euros from the late architect and painter Gabriella Pizzochero Salvini, who died in 2021 and was also a benefactress famed for her works of art (La Provincia, 2021).

1.2.1. Historical Centre of Como and History of the Church

There is no definite information available about the church's foundation date; however, the lack of precision has given rise to various theories. The most credible estimate for this old church is that it was constructed in the second half of the eleventh century during the reign of Rainaldo, who died in 1084. (Catalano, 2004). The first mention of it dates back to 1144. Aesthetic similarities, particularly with the Basilica di Sant'Abbondio in Como, erected around 1070, where the same cylindrical pillars of the nave and the motif of the two bell towers are evident, as well as with the Abbey of San Giovanni in Vertemate, founded in 1084 when Rainaldo participated, confirm this chronology (Catalano, 2004).

During the site visit, there were memorial information boards for the church and the surrounding structures, which described the changes that occurred to the space that the church once occupied. The church was constructed with a "Broletto," which is derived from the mediaeval word "Brolo," which means "a field or garden encircled by walls." Figure 2 depicts the initial shape of the church and its geographical location with the surrounding structures in the 11th century (Monument Information Boards, 2022).

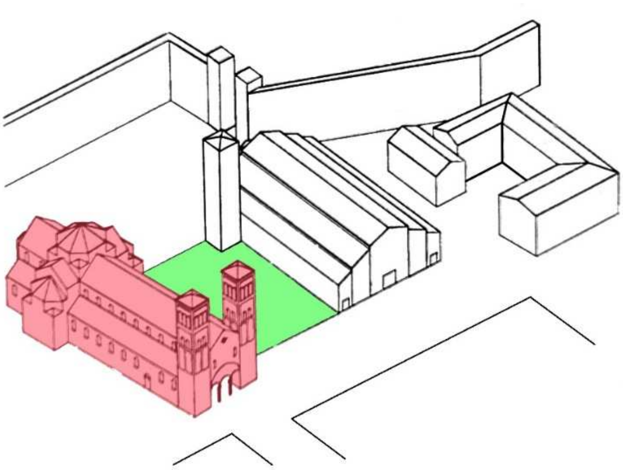

Figure 2 – San Giacomo Church in the 11th Century

In the 11th century, the Lombardian Communes gained independence from the Bishop of Como's feudal control. Frederick Barbarossa signed the Peace Treaty of Constance in 1183, granting the Lombard League Communes more administrative, political, and judicial power. Communes were formed to grant full freedom and were named "Broletto" to symbolise a connection with "Brolo" (Monument Information Boards, 2022).

However, due to the increasing number of civic engagements during the first half of the 13th century, the building at the top of Figure 3 was deemed too small for the purpose for which it was built, and construction on the Praetorium Palace ("Palazzo del Pretorio"), which was to become the home of the local High Official, began. As a result, the "walled garden" evolved into a courtyard surrounded by a majestic, mediaeval façade (Monument Information Boards, 2022).

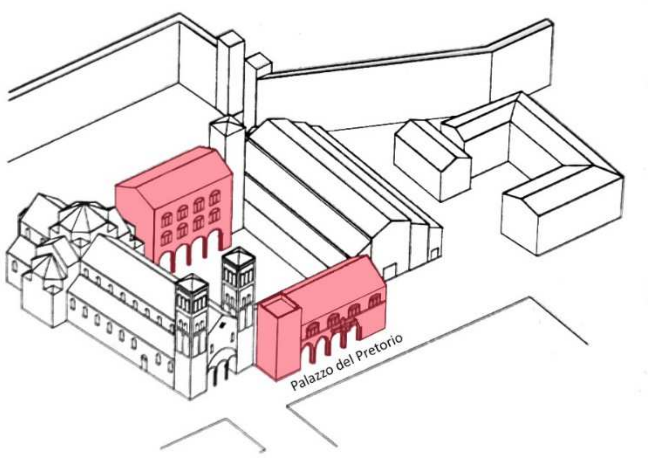

Figure 3 – San Giacomo Church in the 13th Century

Figure 4 shows that a substantial portion of the Broletto was removed so that construction of the Praetorium Palace could take place. Originally, the Broletto reached beyond the Duomo. The Praetorium Palace and the Duomo underwent the majority of the alterations during this process. During this time, the church of San Giacomo did not undergo any changes and remained in its original state (Monument Information Boards, 2022).

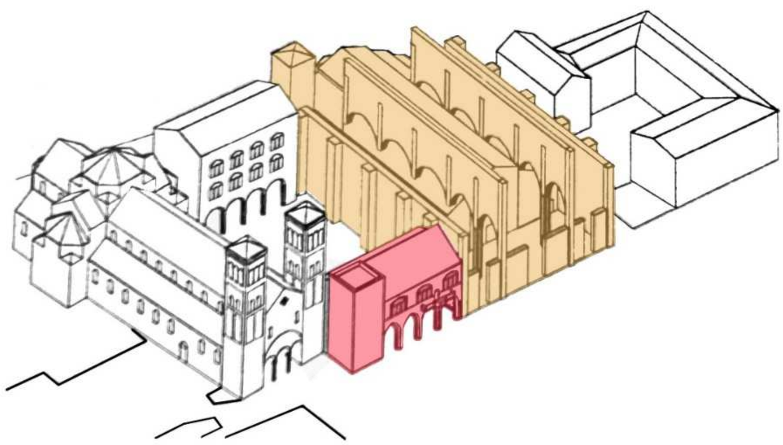

Figure 4 – San Giacomo Church in the 15th Century

Religious architecture triumphed over ordinary civil engineering in the construction of the Duomo. The existing early-Christian cathedral, the Basilica of Santa Maria Maggiore, which may have had five naves, was narrower than the new cathedral. Its southern wall was preserved, and the expansion project continued northward, towards the Broletto. The building began in the east, from the transept. Because the façade was designed to be aligned with the Broletto, the last bay, closest to the door, is shorter than the others. A portion of the Broletto was later removed to make way for the Duomo's northern bay, as shown in Figure 5 (Monument Information Boards, 2022).

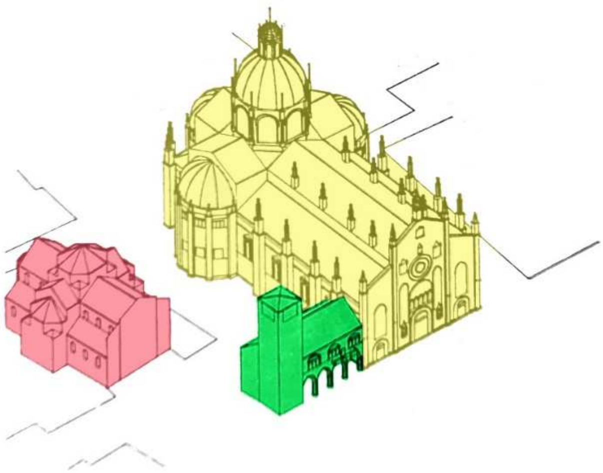

Figure 5 – San Giacomo Church in the 20th Century

The municipality paid for the restoration work associated with the second intervention in 1578, which included demolishing the area between the façade and the first five bays and repurposing it for public use, as shown in Figure 6 (Catalano, 2004).

Figure 6 – Satelite 3D View of San Giacomo Church and the Broletto Area [Source: (Google Maps, 2022)]

1.2.2. General Information About Como

Despite being in the region of Lombardy, Como serves as the administrative capital of the Province of Como. Due to its proximity to both Lake Como and the Alps, Como is a particularly well-liked tourist attraction. The Duomo, which is the administrative centre of the diocese of Como; the Basilica of Saint

Abundius; the Villa Olmo; the Tempio Voltiano Public Garden; the Teatro Sociale; the Broletto ("which is surrounded by the cathedral of Santa Maria Assunta, the church of San Giacomo, and the Palazzo del Pretorio, Figure 8"); and the 20th-century House of Fascism are just a few of the city's numerous monuments, including numerous churches, gardens, museums, theatres, parks, and palaces (Wikipedia, 2010).

Figure 7 – Satelite Plan View of San Giacomo Church

Figure 8 – The Location of San Giacomo Church in the Broletto Area

Figure 9 – Orthophotos with Photogrammetry for San Giacomo Church

1.3. DESCRIPTION OF THE PROBLEM WITH HYPOTHESES

According to the official website of the province of Como, La Provincia (2021), the repair work on the church of San Giacomo started after a meticulous and in-depth study phase. According to the diocese of the church, the interventions would most likely be extensive and complex. In a message, the diocese noted that the restoration will be done with innovative techniques and with the attention and care that the basilica deserves.

In terms of interventions, the building site anticipates the employment of cutting-edge digital technology, while architectural choices will allow the original materials to be conserved. As a result, the stone slabs that currently cover the roofs will be conserved by particular treatments that will extend their usable life, for example. And, from an ecological standpoint, this is the best option because it avoids disposing of them and replacing them with fresh stones from distant quarries. In addition to the installation of an efficient heating system to minimise energy usage inside the church.

These advanced and non-invasive methodological and design choices for the restoration of the church will fully achieve their objectives through a broader reflection on the role that such a significant monument could have in the urban system, and without forgetting the further achievable goals, such as the integration of the cultural offer, the return on investment in conservation, and cooperation between the actors of the local economy.

1.4. SCOPE OF WORK AND OBJECTIVES

For the purposes of this study, the scope of the work was limited to the roof portion of the church, which encompasses the roofs that are located over the nave, transepts, and apse, in addition to the roof that is located atop the bell tower. Although the church has many components that call for the development of an HBIM model, this study focused solely on the roof. In total, there were four sections to this conclusion. See Figure 10.

Figure 10 – Scope of Work (The Roof Over the Nave, Transepts, and Apse)

As a result of the creation of the roof model, the objectives of this model are to have documentation for the work that was done and to store all of the metadata for all of the elements in a single reservoir. Additionally, this model can assist in so many applications, such as the design of a maintenance plan, interventions, existing load analysis, and new sections if they are required. Furthermore, this model can be used for managing the heritage while in the operation phase.

1.5. STATE-OF-THE-ART OF THE STUDIES CARRIED OUT SO FAR

Since historical monuments are considered a part of the world's heritage, countries are attempting to preserve a portion of their history through them. This can be done by mandating the preservation and restoration of these monuments through a Top-Down diffusion strategy (Succar, 2014), see Figure 11, in which the governments first mandate the adoption of the restoration in their local governorates through local businesses, which will oversee a number of task-oriented sub-consultants during the restoration process. These historical standards, as well as comparable standards from around the world, outline the best practices for managing and conserving historic and traditional structures from a governmental standpoint through the publication of historical standards like the British Standard (BS 7913, 2013) or the code of cultural heritage and landscape in Italy (Decreto Legislativo, 2002). Along with the relevant techniques, such as surveys, management, and supervision, these regulations also discuss the technicalities and importance of these monuments (Edwards, 2017). The objective of HBIM is to bring these worldwide standards into practice for implementation, in addition to those that have been made public by organisations like ICOMOS (2022). On the other hand, the process also works the opposite way, with companies defining norms and using what they've learned to update regulations using innovative approaches.

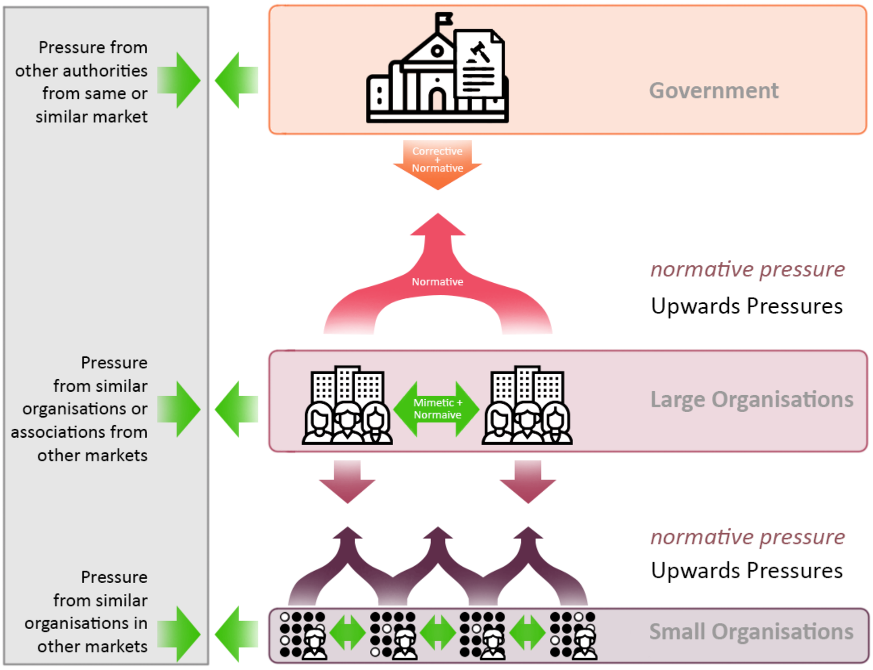

Figure 11 – Top-Down Diffusion Strategy for Mandating HBIM Regulations

The process of preserving a heritage building can be achieved through the creation of a three-dimensional model using model authoring software, which can contain all the thematic information about the physical building. The software used is optional as long as it includes a reservoir for storing all of the metadata generated during the scan-to-BIM process. In order to collect all the data required for the creation of the model, the level of detail needs to be taken into consideration to capture the required geometrical features of the building, which includes the laser scanning model, the photogrammetry, and the heritage documentation (Volk, et al., 2014). An extra method that can be used in this procedure is the LIDAR, as described by Baik (2017), which uses a combination of all the methods to get as much information as possible from the heritage of old Jeddah, Saudi Arabia.

Buildings vary in usage, such as residential, commercial, and governmental, as well as age (new, existing, and heritage) (Volk, et al., 2014). A crucial part of developing a heritage (HBIM) model is to know that it is completely different from an existing BIM or EBIM. The key difference is that the EBIM models the building as it is intended to be, while the HBIM models the building as it is in real life (Littlefield, 2017). According to Bhatla et al. (2012), a model can be simply generated using a handheld camera. However, the study concluded that it is not suitable as it generates models with a significant difference in the length of the object. The process of collecting the data was discussed several times in many publications (Murphy, et al., 2013) (Cheng & Jin, 2006) and (Pidduck, 2017). The collected data requires extensive research into the historical documents of the building. The main goal is to collect more information about the heritage from credible sources. For example, one such research used the documents provided by the Renaissance architect "Andrea Palladio" to give details about the type of architecture used in the building (Quattrini & Baleani, 2015), and another used the historical records archived in the historical library for a building (Banfi, et al., 2019).

After collecting the data, a Scan-to-BIM process is initiated, which includes manipulating the data collected into a model (Banfi, et al., 2019). The model can be modelled in so many ways depending on the complexity of the geometry. A complex method can require the use of the artificial intelligence package inside Dynamo to handle a point cloud file by clustering, Alpha shape, and ICP Pointcloud registration (Mohareb, 2019) or by detecting the point cloud elements to generate a NURBS model that can be converted into an HBIM (Banfi, et al., 2020). According to Fornos (2015), the same method was used in the chapel of La Virgen de la Antigua in the Seville Cathedral.

Another approach is for less complex projects where a digital library can be generated to model the elements (Murphy, et al., 2013). The modelling technique can be represented by using parametric geometries (Trillo, et al., 2021), and the model incorporates all types of necessary information about the monument, including measurements, locations, coordinates, and so on in both visual and alphanumeric formats. This has proven to be a valuable resource for integrated heritage management (Rua & Gil, 2014). The model must replicate the existing building as it is built, and it must be capable of storing all relevant maintenance information, including the identification of all deficiencies (Talon, et al., 2017).

After generating the HBIM, there are plenty of applications that can be obtained from the model, considering it as a digital twin to the real one, and plenty of uses are described in the work done by Khajavi et al. (2019). One of the many applications of HBIM is to check the safety of structural elements like those in masonry historical constructions (Roca, et al., 2010). Another example can be generating a maintenance plan with construction safety management and scaffolding assembly (Biagini, et al., 2016). Moreover, another application can be the use of sustainability in a heritage building (Žurić, et al., 2020). Many other applications were assembled in the work of Deng et al. (2021) where they were categorised into levels of use.

1.6. METHODS OF RESEARCH

The methodology of qualitative research serves as the basis for the underlying philosophy of this investigation. This specific method was chosen because it offers a way to investigate the feasibility of constructing an HBIM model from a point cloud file as well as to reverse the engineering process of design in order to examine the roof's resilience in the face of the stresses to which it is currently being subjected. This methodology was chosen for the research project in order to obtain reliable results that are relevant to the aims and objectives of this investigation. The data was gathered through the use of laser scan point cloud files, orthophotos created with photogrammetry, tape measurements obtained from site visits, aerial videos, and 360º videos (Figure 12). Every one of these sources was gathered either by myself or by other researchers who were also researching the same church for the remaining parts. By sorting the data, we were able to collect them and then upload them to a cloud repository that all of the appointed parties could view. After gathering the necessary information for the process of modelling, the files needed to be analysed and checked again to get rid of the redundant information and the data that is of no use. Following data collection and analysis, the modelling process began by generating segregated models that included ownership of the various parts of the church. The roof of the church was the focus of this research, and as a result, a model of the roof was developed. As for the other models, they were linked with the other models using the shared coordinate system. By making a fishbone analogy of the process (Figure 13), you can see the whole process from the beginning of the investigation until you reach a final product that can assist in analysing loads, redesigning sections, applying interventions, and much more.

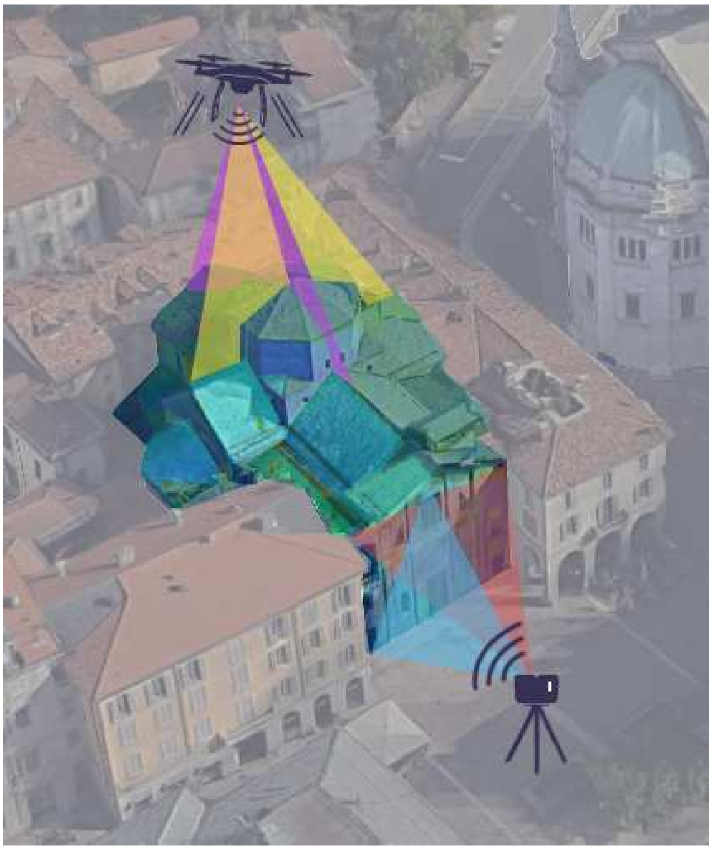

Figure 12 – The Digital Scanning Process for Data Collection

1.7. BRIEF DESCRIPTION OF THESIS OUTLINE

The thesis will be divided into seven chapters. Each chapter will cover a different aspect of the process of creating a historical building information model, beginning with Chapter 1, which includes an introduction to the history of the church, the historical centre of Como, a description of the problem and the objectives for the thesis, and an outline. Chapter 2 will follow that to introduce the followed workflow for assessing a heritage site as well as the HBIM modelling and investigation procedures, in addition to the analysis of the deterioration and how that affects the safety of the structure. Following that, Chapter 3 will go into the architectural features of the church, the composition, and the arrangement of the church elements, in addition to the longitudinal and transversal sections for the key parts of the case study. Chapter 4, on the other hand, will discuss the attempts carried out to produce an HBIM model by mapping the data gathered from all the possible digital and traditional sources, which will assist in understanding the application that will take place in Chapter 5, which is to export an analytical model from the HBIM model, extract all the imposed loads, and reassess the existing frames against the existing loads. Finally, Chapter 6 will wrap up the completed work and will pave the path for future research and ideas. For a concise arrangement of the chapters, see the infographic in Figure 14 for the thesis general outline.

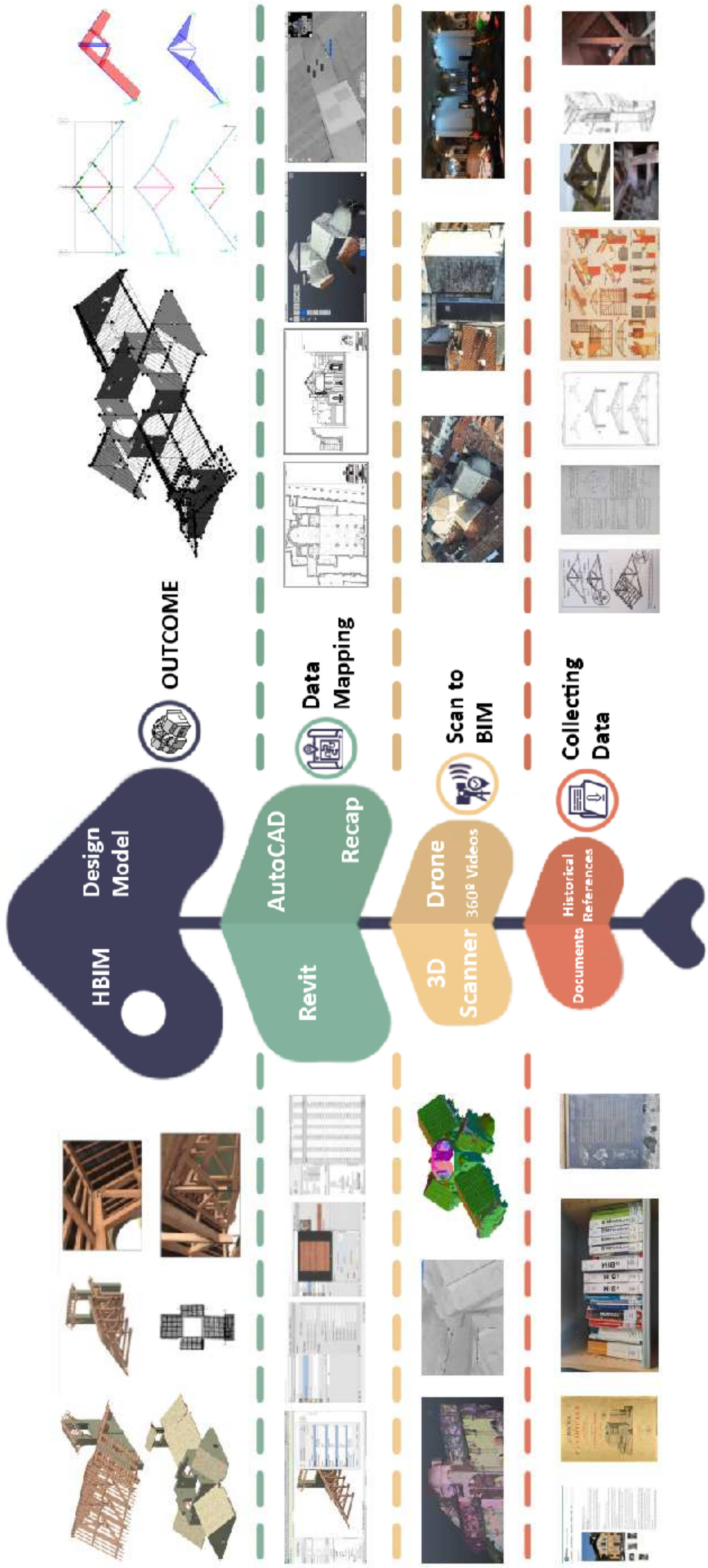

Figure 13 – Fishbone Diagram for the HBIM Modelling Process

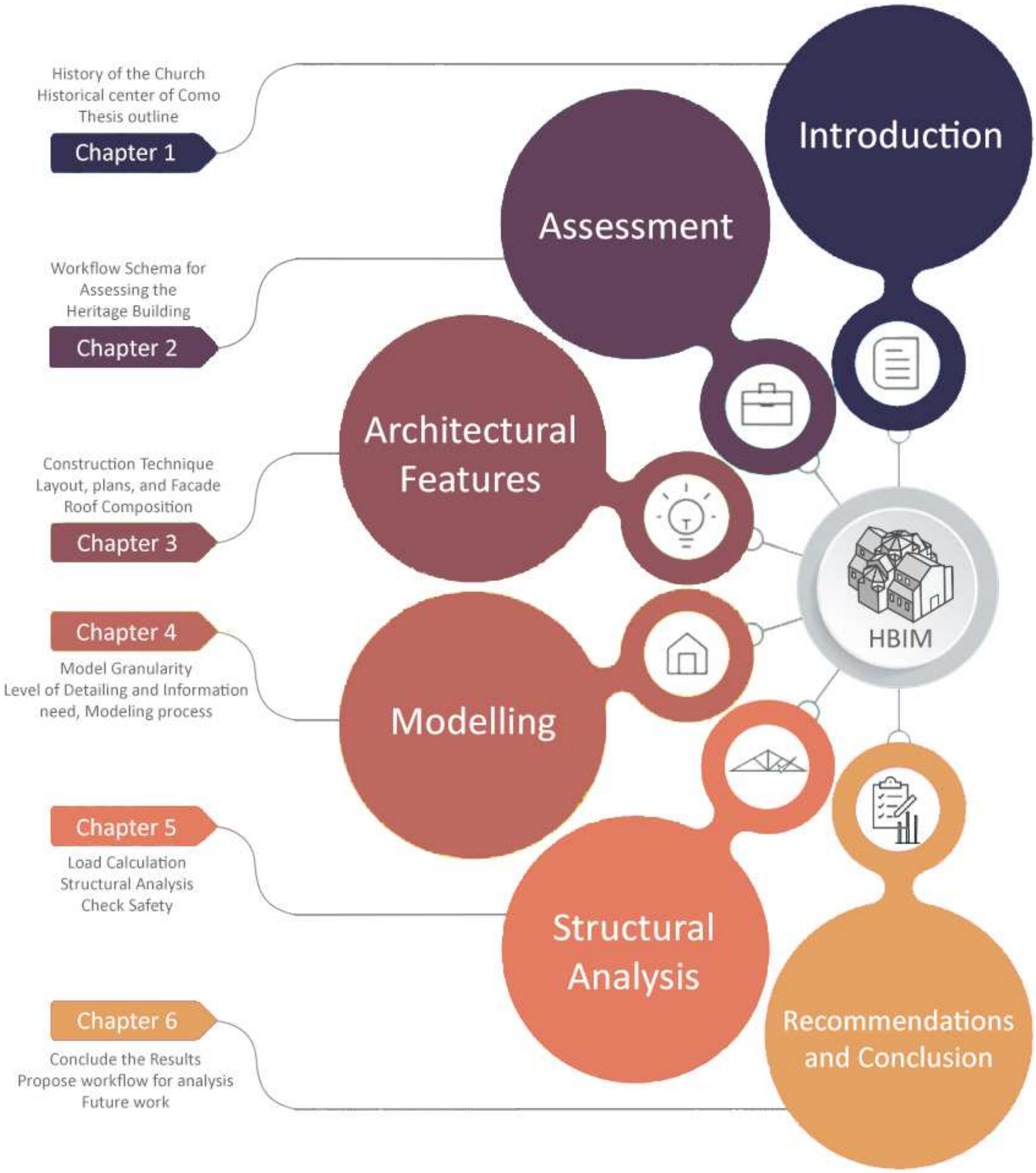

Figure 14 – Thesis Outline Infographics

2. ASSESSMENT OF THE HERITAGE BUILDING

The assessment of a heritage model is a lifecycle process that may follow the asset for as long as it is in existence, and the asset information is not only a concern during the delivery phase of the facility. In Chapter 4, we will discuss the Asset Information Requirements (AIR) and how they are required through the lifecycle of the heritage BIM project. In this chapter, we will discuss the assessment process for a heritage site and how that can affect the process of creating a BIM model.

In a BIM project, there is usually a document called the Organizational Information Requirements (OIR). This document describes the information that the owner needs at a strategic level for the asset, the project, and other business functions and needs. It also helps the owner figure out what information he needs to meet his needs. In this scenario, we may think of the owner as the government or the committee in charge of conserving the heritage because the owner has certain standards that must be met, and these requirements must be in accordance with the country's local and regional standards.

The OIR sets out the value of BIM and proper information management to the owner and has to be compiled after data collection. The project teams must respond and make sure they drive value to the asset while doing so. These OIRs constitute the basis for the AIR and the Project Standard and Information Model Uses.

With the end in mind and to fulfil the OIR, the asset information team expects the project teams to plan, manage, and deliver asset information on the occurrence of any of the following event types:

- At every stage of the heritage plan of work.
- Inspection of the heritage asset.
- Maintenance work on the heritage asset for both reactive and preventive maintenance.
- Major work on the heritage asset, upgrade, retrofit, repurpose, and general improvements.
- Minor work on the heritage asset, minor repairs, and component replacement.
- End-of-life works: decommissioning, demolition, deactivation, and preservation.
- Asset-related planning and analysis.
- Changes in the regulations applying to the heritage asset.
- Change in the value of the heritage asset.
- Change in the information demanded by a regulator.
- Change in the OIRs relating to the heritage asset.
- A change in the ownership, operator, or maintainer of a heritage asset.

2.1. ASSESSMENT WORKFLOW SCHEMA

The assessment process, Figure 15, shall take place on a lifecycle scale as mentioned previously and can be divided into two main processes: the first one is concerned with geometric modelling in authoring software, and the second is related to ensuring the safety of the designed sections. The rationale for this separation is that the restoration process might occur in stages, with various options for deciding on the appropriate intervention or material. And for each decision, an assessment process needs to take place.

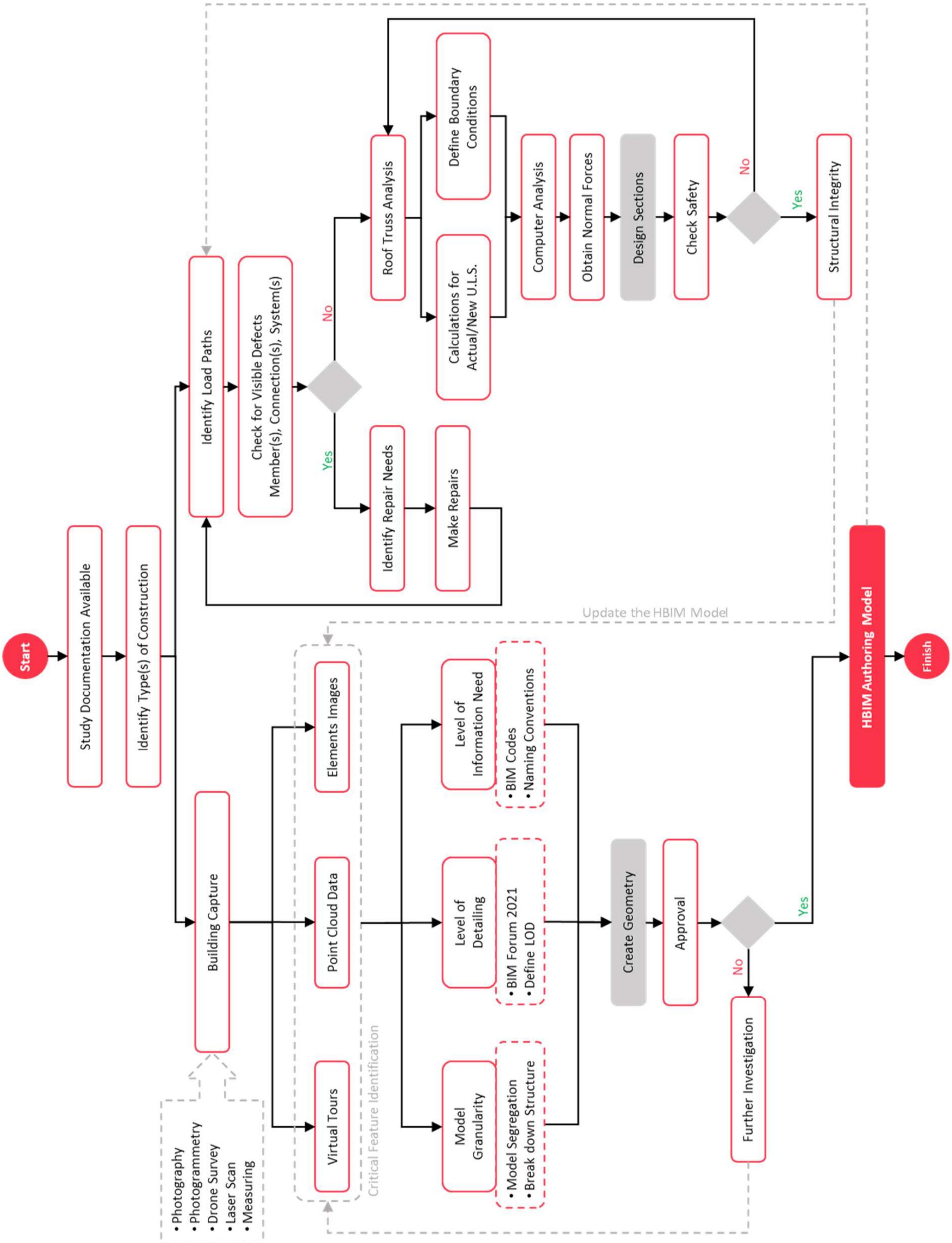

Figure 15 – Assessment Schema of Heritage Building

The whole process needs to be digitalized in order to facilitate the automation of the workflow and help organise and prioritise the asset development and management strategy. BIM is intended to support planning activities such as organising and prioritising the development of an asset and the corresponding management strategy within the context of the heritage asset, which includes the information that the model must include, and that any associated use must produce information aimed at supporting project planning, the breakdown of design and construction works, and assessing their economic and environmental costs within the regulatory context.

2.2. DIGITALISATION OF THE PROCESS

It is expected to benefit from BIM for the simulation of demand, space usage, and conditions in line with its vision for the built environment at the space, asset, and urban scale. This could include things like computer simulations, accessibility checks, visual checks, and a look at how wind, rain, dirt, sun, and other environmental factors affect the building.

Digitalising these processes facilitates executing them through integration between multiple software in an open BIM environment. Using model authoring software to generate the asset model, which includes all the required information to generate all sorts of simulations and analyses, can also aid in the redesign of the assets in a way that promotes consistency, clarity, and economy in the definition of spaces, structures, systems, and components.

Digitalisation supports quality management in the project by incorporating information related to spatial coordination, codification, code compliance, feasibility, and compatibility. This method can help plan, discuss, and understand construction activities. It can also use information models to simulate the construction sequencing and auxiliary elements in a way that saves time and money and makes it easier to make decisions.

2.3. HERITAGE DIGITAL TWIN

A "Digital Twin" is a dynamic model of an asset, with the input of current performance data from the physical twin via live data flows from sensors and feedback into the physical twin via real-time control (MottMacdonald, 2022). The information model has to be a credible, updated, complete, and economical representation of the asset that allows its extension and integration into a digital twin platform and provides the basis for that digital twin model. A Project Information Model (PIM) can be cleared of any non-relevant data and become an Asset Information Model (AIM) that can in turn be connected with sensors and actuators.

The AIM contains relevant information and the right structure to support decision-making in the Digital Twin Platform. Asset Information Models contain the right information about facilities and equipment to support a wide range of applications. One of these applications is the digital operation and maintenance of heritage assets. The digital twin can also help plan and execute minor upgrades, fixes, and refurbishments to the asset. This requirement extends the use of BIM beyond whole-asset delivery to every activity that modifies a completed or operational facility. The use of BIM can be planned so it brings value to those activities and delivers an updated AIM.

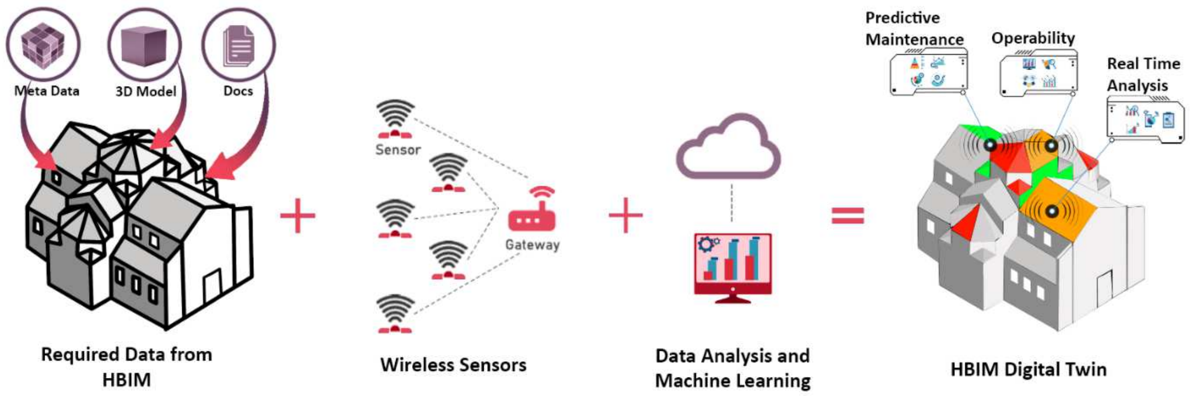

Figure 16 – Digital Twin of a Heritage Building

The finest potential digital twins will be produced using hybrid analytics, which combines machine learning-based analytics with physics-based techniques. These hybrid analytics can improve the experience for the user, the solver, the model library, and the accuracy of the predictions made by the digital twins. Furthermore, the model can be used to predict maintenance by strategically installing Wireless Sensors Network (WSN). Figure 16 depicts S.H. Khajavi's (2019) approach to the essential components of creating a digital twin of a building using the WSN for BIM and how to link them using a cloud server that can handle machine learning-based data analytics. The same technology may be used to help detect any roof instability, and an interactive library can also offer a way to address an issue and save money on the asset's long-term operational budget.

3. ARCHITECTURAL FEATURES OF THE CHURCH

3.1. STRUCTURAL CONFIGURATION OF THE CHURCH

3.1.1. Composition of the Church

The church is composed of three main naves, and the bell tower is situated to the left of the front façade. Outside of the original structure, there are still three apses that have been embellished with double ferrule arches, see Figure 17. Inside the original structure, there are four capitals and the symbols of the Evangelists in the entrance hall (Catalano, 2004).

Figure 17 – The Three Apses of the Church

3.1.2. The Bell Tower

In the seventeenth century, a defence tower of the walls in the northern half was raised and modified to create the bell tower. This tower reached almost the same height as the roof of the church at the time of its construction. The bell tower underwent several alterations throughout the eighteenth century, which resulted in it taking on its current shape, see Figure 18 (Catalano, 2004).

Figure 18 – The Bells Tower Location

3.1.3. Structure of the Roof

The king post method was extensively used for the construction of the roof's supporting structures. A standard mortise and tenon joint may be found in the connection that exists between the king post and the tie beam. In addition, a stirrup made of iron is supplied so that the joint may be strengthened even more. The principal rafters and the king post are joined together by cutting a tenon into the principal rafter and a mortice into the head of the king post. A bridle joint has been supplied to facilitate the connection between the principal rafter and the tie beam. Mortise and tenon joints are used in the construction of the joints between the king post and the strut (Gopi, 2010), see Figure 19.

Figure 19 – King Post Wooden Connections and Metal Brackets

3.2. FEATURES OF LAYOUT AND PLANNING

3.2.1. Layout Arrangement of the Plan

The remaining church interior has a Romanesque chancel as well as an apse in the shape of a semicircle that contains seven niches. The altar that was built in the eighteenth century has been removed. Over the top was the San Giacomo martyrdom, which is credited to Giovanni Paolo and Giovanni Battista Recchi.

Giovanni Battista Colomba, a painter from Switzerland, is credited with painting the Pentecost in the bowl apse somewhere in the seventeenth century. The picture of Saint Philip Neri in adoration of Christ Crucified (1680) was created by Giovanni Stefano Doneda, also known as Montalto. It is located in the chapel on the right side. There is a painting of Saint Joseph from 1740 that was done by the Venetian painter Giovan Battista Pittoni and can be found in the chapel that is directly adjacent to it (Cattedrale di Como, 2015).

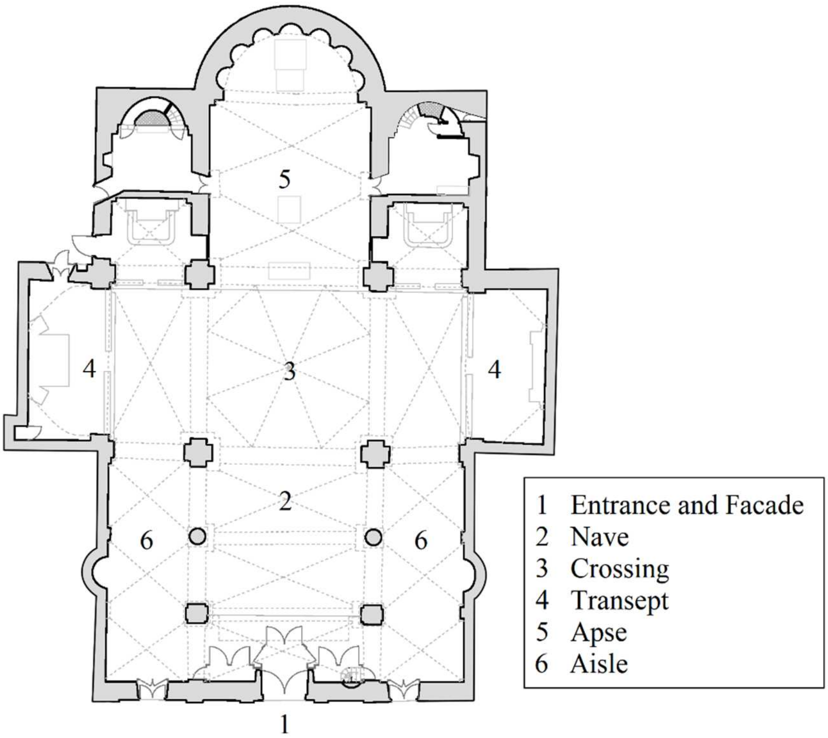

Figure 20 – General plan Layout of the Church

3.2.2. Longitudinal Sections for Trusses Arrangement

By examining the church's longitudinal and transversal sections, as shown in Figure 21 and Figure 22, you will be able to identify the configuration of the truss frames that make up the roof. You will also be able to discover the link that exists between these frames and how they are situated with respect to the vaults that are located underneath them. If you look at the parts, which demonstrate their respective places, you will be able to tell the difference between the old frame and the new ones as well.

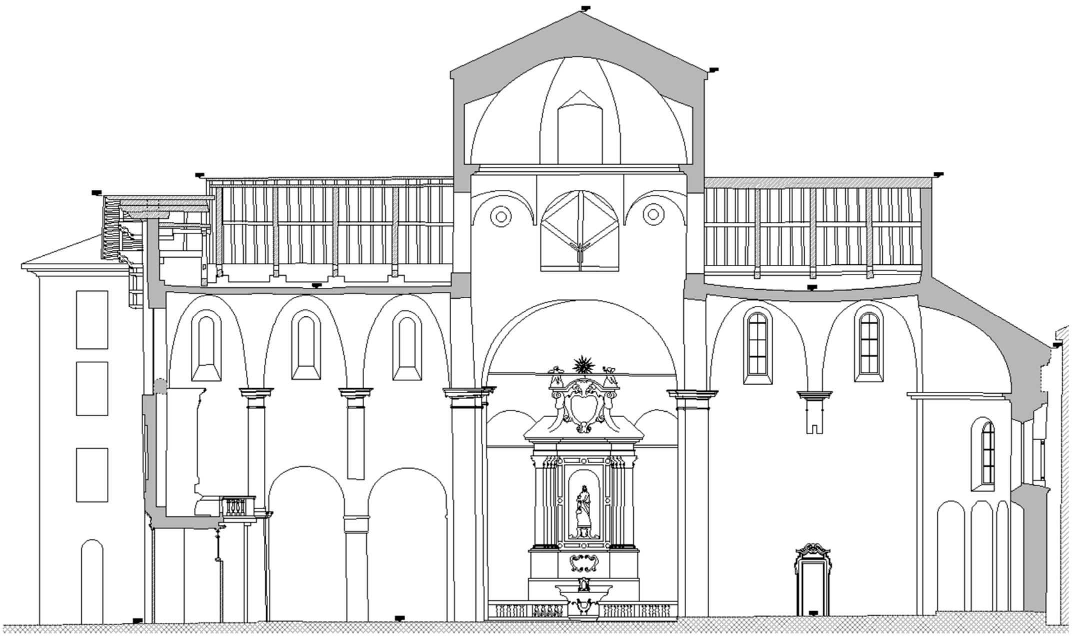

Figure 21 – Longitudinal Cross Section of the Church

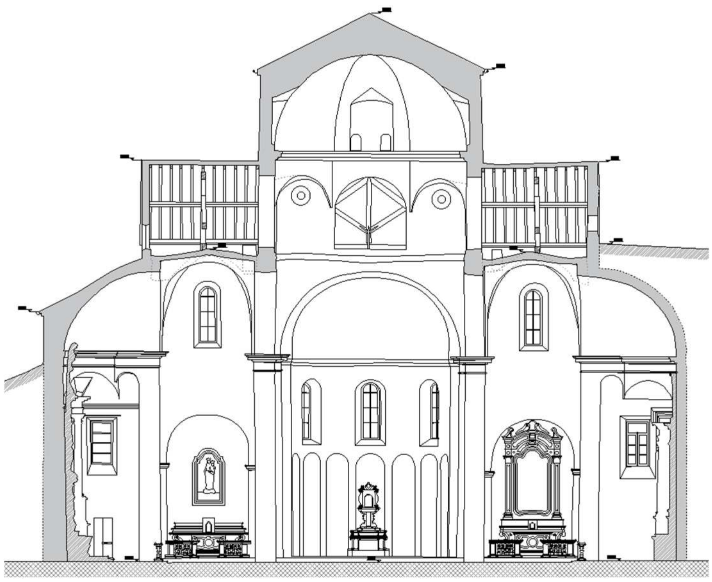

Figure 22 – Transversal Cross Section of the Church

On the other hand, Figure 23 captures the shape of the new frame that was applied in the first intervention that was carried out in the year 1578, whereas Figure 24 represents the original frame that was still present from the initial shape and was still maintained by the façade brick wall that carries all of the loads subjected to it.

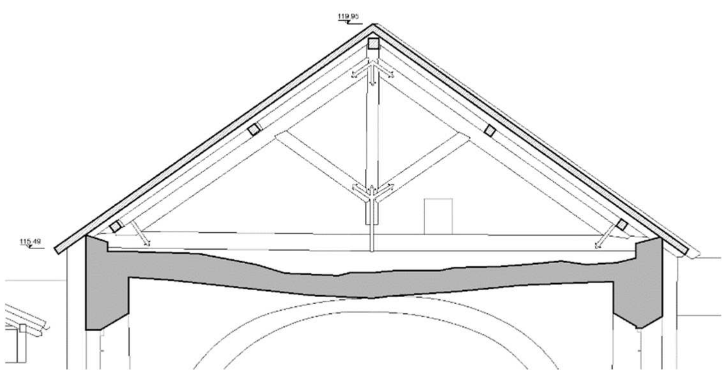

Figure 23 – Section Elevation for the New Frame

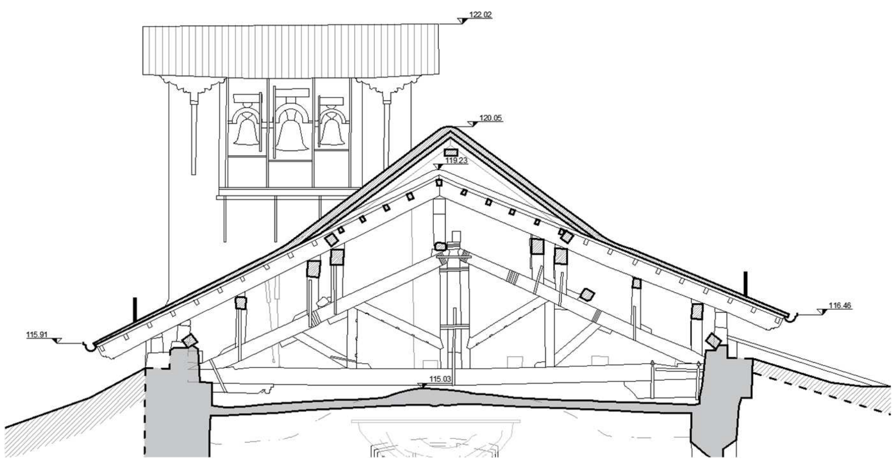

Figure 24 – Section Elevation for the Old Frame

3.2.3. The Façade Wall

The gabled façade was constructed in accordance with the design that was developed by the architect Giovanni Antonio Piotti of Vacallo. The large window, the ocher-coloured plaster, and the decoration with fake marble are the distinguishing features of this church. The triumph of the cross is located at the uppermost portion of the building's façade, Figure 25. You will notice a simple bell tower serves as the capping for the roof as well (Cattedrale di Como, 2015).

Figure 25 – San Giacomo Church Façade (Left: Photogrammetry – Right: CAD Drawing)

3.3. KING POST TRUSS IN THE ROOF

3.3.1. Introduction King Post Truss

The used system in this church is a king post truss. The usual covering span for this truss ranges between (5 to 9) meters. Trusses are often used when there are no available intermediate supporting walls for the purlins. The placement of the trusses always depends on the weight of the roof, the truss material, the span, and the location of the cross walls (Binu & Rajesh Kumar, 2021).

The central vertical post, commonly referred to as the king post, supports the tie beam in a king post truss. To prevent the major rafters from bowing in the middle, the struts, or inclined members, are necessary (Figure 26). The system can be used economically within the allowed span, but our studied truss has a span of 10 meters, which could lead to larger cross-sections and possibly more stress (Binu & Rajesh Kumar, 2021).

3.3.2. King Post Details, Connections, and Pitch Ratio

The frame consists of several elements. Table 1 will list each element of the system and give a clear explanation of how it works in the system (Burrell, 1889):

Table 1 – King Post Elements

Element Name	Definition and Function
Principle Rafter	slanted timbers that are framed into the tie beam at the lower end and the head of the king post at the top end to support the purlins.
Common Rafter	These are the roof boarding's direct backers. They typically run from the ridge part at the top of the frame to the frame supports, with purlins supporting them at one or two locations.
Strut	Components that are attached to the lower end of the king post and the top end of the principal rafters to avoid deflection.
Purlin	The horizontal timbers that go across the backs of the principal rafters support the common rafters in turn at or near the centre of their length.
Ridge Beam	This is the timber beam that runs the entire length of the roof and is supported in a cut-out groove at the top of the king post. The common rafters are attached to the ridge beam where they rest against it.

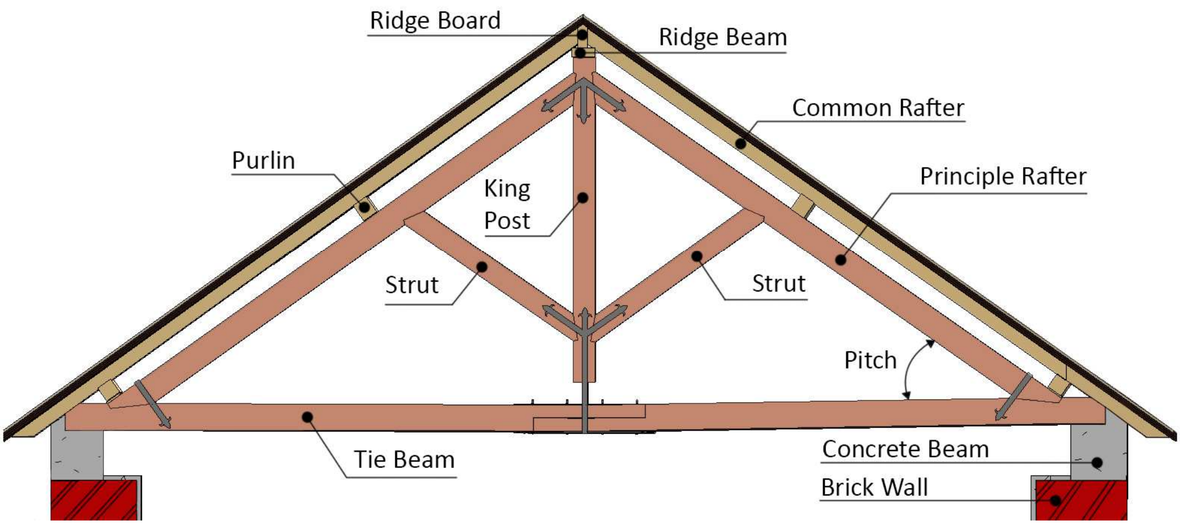

Figure 26 – King Post Truss Elements Arrangement in the Church

According to the Traditional Dwellings and Settlements Working Paper Series (1989), the pitch of a roof is the ratio between the height of the frame and half the span of the frame. Usually, the king post pitches are in the ratios of 2:1, 5:3, or 10:3. In the case study we have, the deformation of each frame was different from the deformation of the other frames; they were modelled based on their real pitch, but throughout the load analysis process, the normalised value was taken into consideration. The normalised pitch was determined using the average roof inclination, which was 35º.

4. AUTHORING THE HERITAGE MODEL

4.1. IDENTIFYING THE SCOPE AND BIM DOCUMENTS

The primary goal of this research is to build a heritage three-dimensional model, and in order to accomplish so, we need to draught certain regulations that streamline the creation of the deliverables and manage the process. To specify the needs of the appointing party, a document called the Exchange Information Requirements (EIR), formerly known as the Employer's Information Requirements, is typically generated in BIM projects. This merely specifies the requirements and BIM procedures of the project together with the BIM norms and regulations. The goal of this dissertation is to help project teams understand the expected value of the asset, which in our case is the heritage, throughout its lifecycle until handover, as well as the rules that should guide decisions, project development, and approvals.

The main objectives of the EIR are:

- Make sure that every member of the project team knows what their roles and responsibilities are in the digital delivery workflow.
- Ensure that the appointed parties are provided information in the most efficient manner possible at every step of the project, ensuring the economy of means.
- Eliminate duplicate and unnecessary rework in the project so that no one redoes the work of the other.

By setting a clear and consistent BIM procedure for the HBIM project, in line with the ISO-19650 series of standards, the typical BIM workflow can be benchmarked and measured to evaluate efficiency, speed, and quality. The ISO-19650 series of standards is an international standard of good practice. It sets out the rules for and principles of information management in the broader context of digital transformation in the built environment's disciplines and sectors (BSIgroup, 2020).

In parallel with the EIR document, an extensive document to define the Asset Information Requirements (AIR) also needs to be established. The document defines the information and exchanges required by the authorities to obtain the AIM. The AIR must be satisfied through the fulfilment of the Project Information Requirement (PIR).

Asset information may be exchanged or consumed by generating an AIM as a container with a BIM Level 2 implementation or directly as data in a Level 3 implementation. A list of activities can be identified in the AIR document, which will assist project teams in planning work when specific asset information must be prepared and exchanged. The list can include the following aspects:

- Asset planning, capital investment and life cycle costing.
- Comparison and selection of asset intervention alternatives.
- Cost analysis for the renovation works and its revenue.
- Asset lifecycle analysis.
- Asset demand, use and conditions simulation.

- Energy efficiency and environmental aspects.
- Asset handover.
- Preparation and update of the model digital twin.
- Risk assessment.
- Security, safety and contingency planning.
- Equipment identification.
- Interfacing with regulatory bodies.
- Publication of asset information for use by the public.
- Asset modifications, refurbishment, replacement, reuse/redeployment, disposal, recycling.
- Maintenance, inspection, condition and performance monitoring plans.
- Knowledge management and innovation related to the asset.

4.2. LEVEL OF DETAILING

A very high level of detail (LOD) is required for modelling a heritage model, and LOD500, which is appropriate for as-built models, is the most acceptable level of detail. The elements must be modelled in a site-verified form in terms of size, shape, position, quantity, and orientation for a LOD500 model, along with the non-graphic data that must be provided with these elements (AIA-G202, 2013).

Any data may be immediately accessed from the created model at any milestone of a project developed using LOD500, as long as it is compatible with the minimal data needed for the model element's LOD for that project milestone (AIA-G202, 2013).

Finding a description of how items are expected to be modelled is made more difficult by the knowledge that LOD500 models are defined to be used for site verification since it is not an indicator of increasing the degree of detail for a model. The model can be created using LOD400 and include all the information defining the elements in real life, such as materials, position, number, and shape, as well as any deformation or warping in real life for the elements. A model may additionally include non-graphical data such as the method of construction, material density, sensor positions, dates and plans for operation and maintenance,... etc.

According to the BIM forum 2021 (Bedrick, et al., 2021), a truss frame has to show an actual final truss profile with accurate panel points, bridging and lateral braces, fire protection coating, and any miscellaneous framing about the truss, chord, and web member section profiles are accurately defined, truss layout in coordination with deck fasteners would be confirmed, hold down locations for large bolts.

Also, element modelling has to include the following: fasteners, sealant, truss plates and connection material, nails and fasteners, truss plates, deck patterns and joints, see Figure 27.

4.3. LEVEL OF INFORMATION NEED

This is the level of information required for a purpose in the project, and it shall be defined, particularly in the EIR, AIR, PIR, and OIR. Nevertheless, shall define the quality, quantity and granularity of information required from the model (ISO 19650–1, 2018).

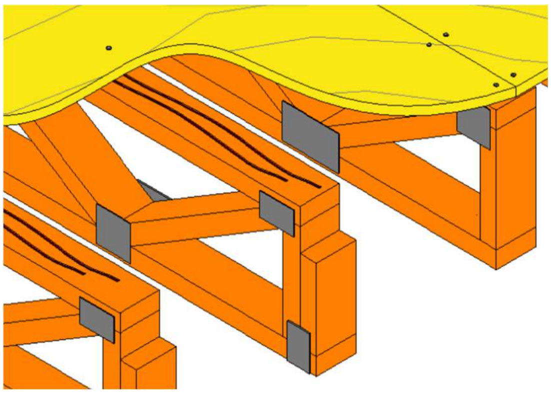

Figure 27 – LOD400 in the BIM Forum, can be used as LOD500 [Source: (Bedrick, et al., 2021)]

The five-scale LOD can take us in the correct direction even if it is not exact in how it defines the model's level of detailing or, should we say, the model definition. Because of this, it is essential to apply a Level of Information Need. The model definition and data accuracy will both improve with the inclusion of the geometry, information, and documents inside our model (Heesom, et al., 2020).

The right amount of information must be delivered and exchanged at every stage of a project. Besides that, it is a must to prevent the production and delivery of too much or too little or incorrect information.

The minimal quantity of information required to satisfy each significant criterion should be used to establish the geometrical and alphanumeric level of information per the requirements. An information deliverable's granularity is not always connected with its significance. However, the model federation strategy is intimately related to the amount of information required (ISO 19650–1, 2018), see Figure 28.

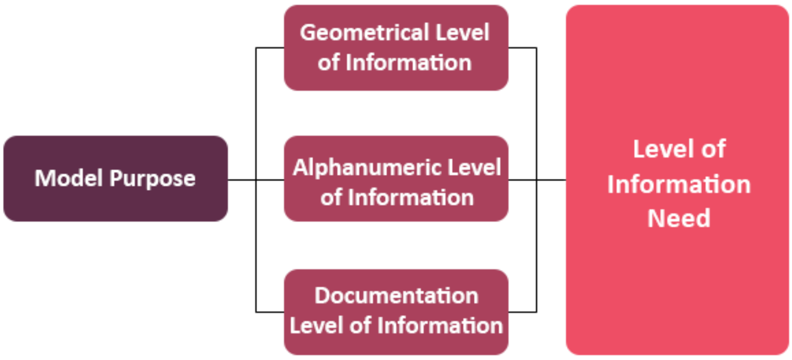

Figure 28 – Level of Information Need Schema

4.4. MODEL GRANULARITY

Making an HBIM supports the planning activities and involves organising and prioritising the development of the asset and the corresponding management strategy within the context of the project. This means that the information model must include, and any associated use must generate, information aimed at enabling and supporting the planning of new assets, the refurbishment of existing ones, the breakdown of design and construction work, and the assessment of their economic and environmental costs.

The goal of the information container breakdown structure and the federation strategy is to aid in planning the information output by various task teams to the necessary level of information need, as discussed in section (4.3.).

The information planning processes should include developing the federation strategy for the model. It should describe the desired division of the information model into one or more sets of information containers. Besides, it needs to be mentioned in the BIM Execution Plan (BEP) of the project. The segregation process can be done by dividing by functional, spatial, and geometrical representations of the information model.

The model in our case study was segregated into many models, one of which was the church's roof, while the other models were separated according to their geometrical representations. All of the models maintained the same coordinates, base points, naming convention, and semantics in order to synchronise the work across all of the divided models.

A system must be followed to preserve the same naming convention for each element throughout the many files and to make data management easier at all phases of the project. Naming conventions are another component of the breakdown. Following the British standard (BS 1192:2007+A2:2016) naming convention criteria, where a fairly systematic procedure is offered, is typically a successful strategy utilised in BIM projects. The approach aids in the naming of BIM containers, which can include a class of a family or whole models (Figure 29). Similarly, another work achieved by Adami et al. (2018) with fewer parameters for the classification system.

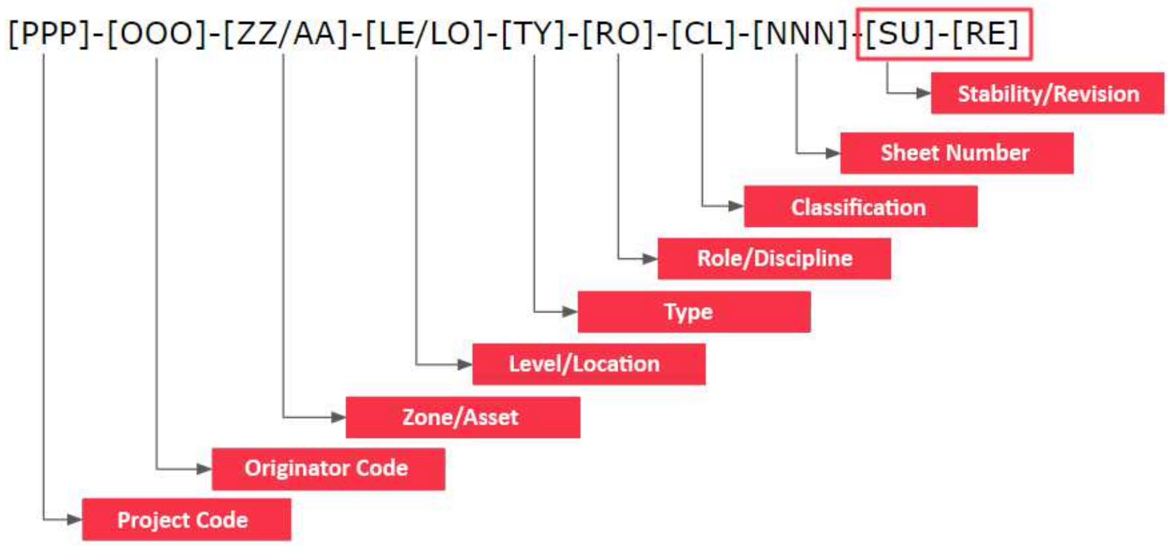

Figure 29 – Naming Convention Breakdown Sample

I was given a file for our case study that included the information exchange protocol as well as the naming convention used during the modelling process. Regarding the naming convention breakdown, all standards were met while creating families, materials, views, and the Revit model as well.

4.5. MODELLING APPROACHES FOR THE KING POST TRUSS

Even though there is no officially sanctioned approach to modelling a heritage model, the vast majority of research points to the creation of generic forms through the use of masses and modelling in-place objects through BIM authoring tools as the best practices. I decided to represent each component in my model exactly as it appears in the real world. This indicates that the authoring software will be able to recognise the components by their appropriate categories, utilise them in the classes that are appropriate for them, and make use of the actual information that is present in the structure that exists in the real world. To do this, I had to investigate the items and construct suitable families to reposition them, making sure that the copies I created were an identical match to the ones that existed before.

In order to provide the families more flexibility, I had to create some parametric features to regulate the material type and the size of each element. Since the primary roof-supporting frames were the focus of the model, it was required to develop a parametric family with a truss category so that it could be positioned in various locations on the floor plan using a single truss' beginning and ending points. In the real world, wooden sections are also warped longitudinally and along the local axis of the sections. The primary deformations that were seen were the torqued sections or deflections in the king post frames, which necessitated the creation of some parameters to control the torque angle and settlements at the support places, see Figure 30.

Figure 30 – Crack (In Green Colour) in Wooden Warped Cross-Sections

In Appendix A, not only is the process of establishing the family for the single typical frame detailed but so are all of the iterations that were carried out in order to get to the final level of the HBIM modelling process.

4.6. USING THE LASER SCAN MODEL

The information given includes point cloud models, which are utilised to build a digital twin of the physical asset. A digital twin is a connected, virtual replica of a physical asset that can be a building, product, or system (refer to section 2.3.). It helps in building an interface that connects the digital and real worlds, Figure 31.

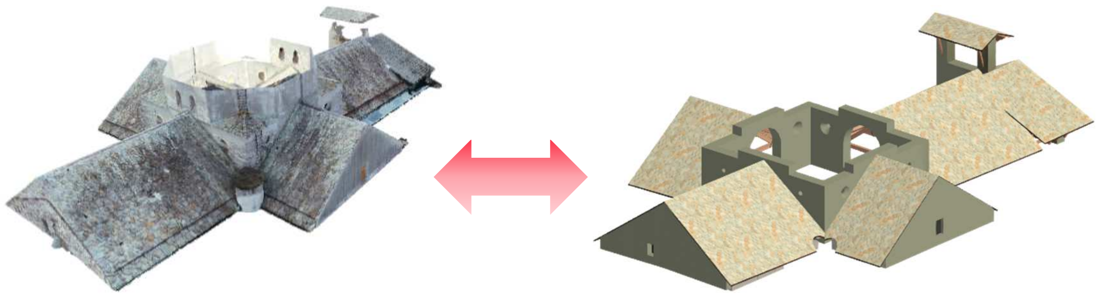

Figure 31 – The Laser Scan Model and Its Digital Twin

By linking the point cloud files into the Revit model, you can get a geometrical representation of the physical model into your virtual model. The point cloud model shares the same coordinates as the Revit model, so the moment it is located, it shows the correct location and geometry of the real elements. However, the model will still lack the information needed to upgrade the accuracy of the elements, as discussed in section (4.3.). That's why we need to define the LOD, the Level of Information Need, and the model granularity to convert the model into a digital twin as we mentioned before.

Point cloud files are always huge in size, and manipulating the file size with a huge number of points is considered risky, especially in the scan-to-BIM process. A way to reduce the file size is to remove the data for the building's surroundings. This may leave the object without context, but without the interference of the excess data, the object can be analysed to the fullest extent (Pidduck, 2017).

The modelling process requires precision and time, and in order to keep the precision, a high tolerance needs to be identified to control the level of accuracy. As agreed with the thesis supervisor, we will have a tolerance of two to three centimetres, which will control the printing size of lines smaller than these numbers. The reason behind that is that if we have a line that is represented by 2 centimetres in real life, and our printing scale is going to be a scale of (1:100), that means the same line will be drawn with a length of 0.02 millimetres, which is a very small object to model.

4.7. THE FINAL OUTCOME OF A HERITAGE MODEL

Several trials were followed to achieve a fully optimised heritage model. The final product of the modelling process is a three-dimensional model that contains the scope of work. The elements were created using the correct naming convention, with fully identified materials that include the mechanical criteria for analysis, such as the isotropic behaviour of wooden elements, the Young modulus, and

Poisson's ratio values. Moreover, all the cross sections were identified, and the families were created following a systematic naming convention to unify the Level of Information Need according to the EIR.

4.7.1. The 3D Geometrical Model

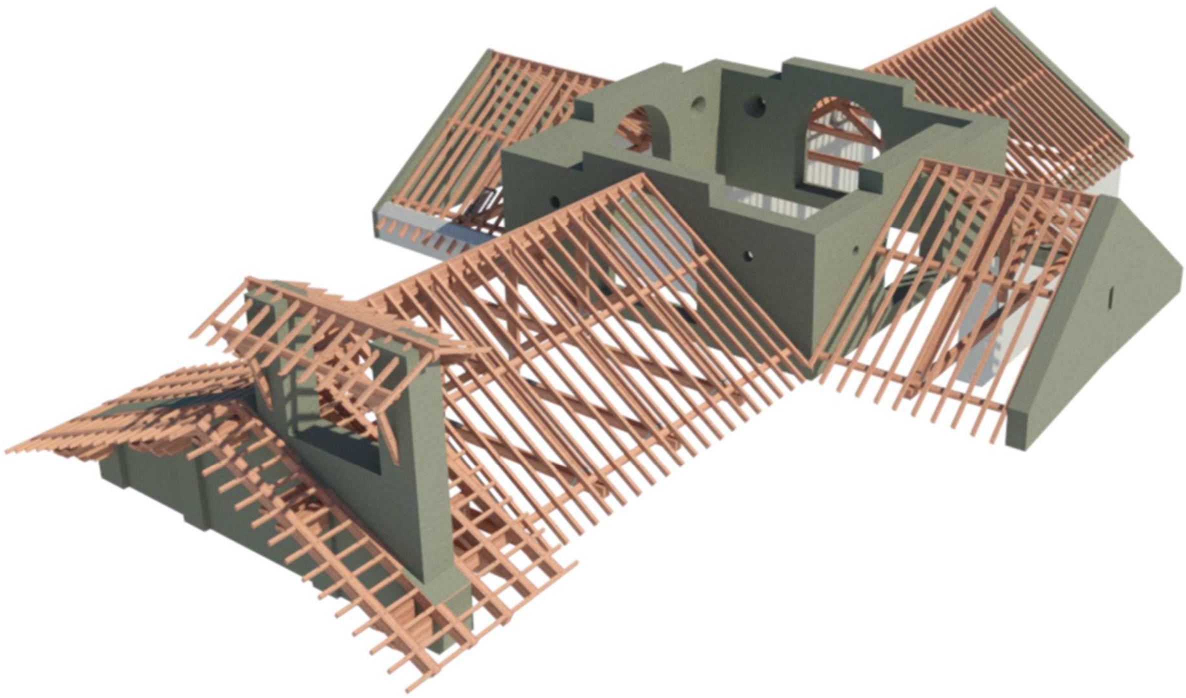

Figure 32 – Wooden Frames Arrangement of the Roof in Revit

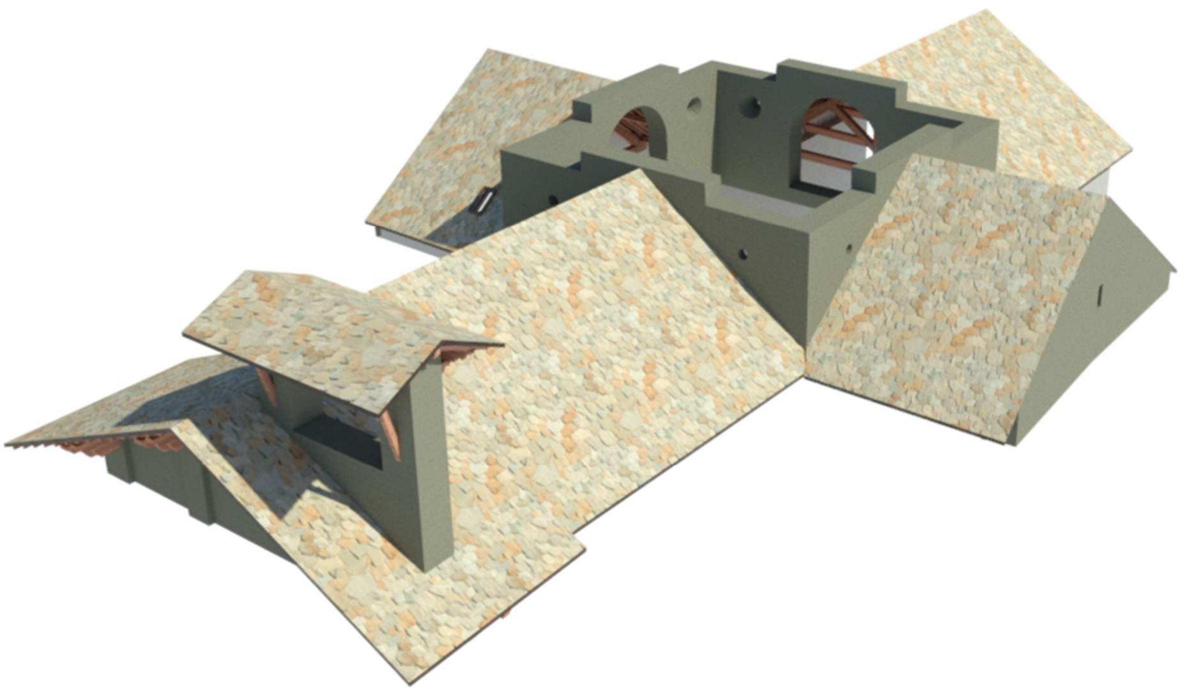

Figure 33 – Stone Slates Tiling of the Roof in Revit

The model was created based on the architectural model outlines provided by another researcher, which were linked using the same shared coordinates of the site location and the point cloud file as well. As a result, all the disciplines were aligned with each other and integrated.

Figure 34 – 3D view for the Structural and Architectural Model in Revit

Figure 35 – Arial View of the Church in Real Life

As seen in Figure 34, the modelled elements (the solid elements) were placed in their correct locations by linking the files together in a federated model. Even though at the time this work was being produced, the remainder of the elements (the transparent elements) were not yet fully modelled, everything was assembled correctly.

You can see the resemblance between the Revit model and the physical building in real life; see Figure 35.

4.7.2. The Truss Family

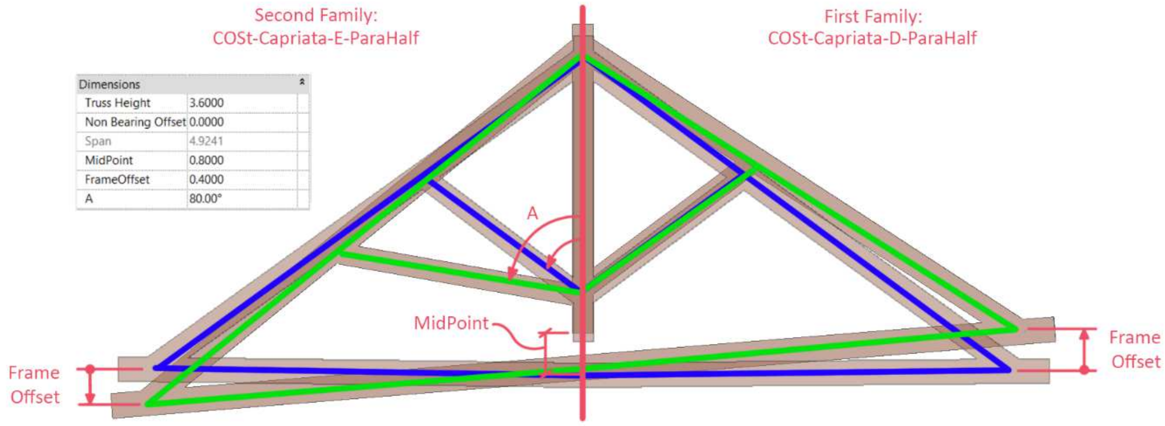

Figure 36 – Original Fame in Real life (Blue) same frame with exaggerated values (Green)

To model the frames one by one, we had to create a family that could facilitate the process. Instead of modelling the elements as a model in place, a decision to assign each element to its original category was taken at the beginning of the modelling process. The family was created as a “Structural Truss” category with parameters to control the dimensions of the family. Refer to the next section (4.7.3.) for more information.

You can read more about the structure of the family in Appendix A in section (A1.4.1.).

4.7.3. The Truss Family Parameters

The truss family contains four parameters that regulate its global and internal dimensions. To modify the truss' height from the reference level to the apex, the "Truss Height" parameter is used. While the length of the truss may be altered on the plan view, because the family is a "Structural Truss," its start and end points can be positioned on the plan view.

The second parameter is "MidPoint," which controls the height of the starting point of the king post from the centerline of the tie beam. This distance is intended to be set for all trusses; however, owing to the various deformations of the trusses, it varied from one truss to the next (see Figure 36). Moreover, "FrameOffset" was made to control the height or depth of frame deformation at the support level. Since we used the middle of the tie beam as the origin of the truss, any deformation will be added to the support locations with an offset distance that controls the displacement in the up or down direction.

Last but not least, the parameter "A" is used to control the angle between the strut and the principal rafter, which is changing in each frame due to the numerous deformations all over the roof.

The rectangular cross-sections of the frame elements can be modified by selection and by modifying the type of the family. There were only two cross-section measurements that ruled the whole roof, except the old frame: (28.0 × 23.5 cm) and (23.5 × 23.5 cm). A wooden rectangular frame family was constructed and allocated to all of the frame's elements. The small section was assigned to the struts and kingpost elements, whilst the large section was assigned to the tie beam and the principal rafters.

4.7.4. Material Assign

Figure 37 – Material Textures in Revit for the Stone Slates and the Red Oak Timber

Materials are an essential component of the modelling process since they influence the colour, setting, and texture of a model's components. As we are reproducing the model from its physical state to its virtual state, we must identify the material as we model and assign the appropriate material to each element. Every model authoring tool used for the production of HBIM must allow the generation of new material properties inside its library; thus, Revit was a solid choice for this job, as we needed to generate materials for the used elements. For instance, we developed two materials for the hardwood and softwood, one material for the stone slates, in addition to other materials for the walls and their finishing layers.

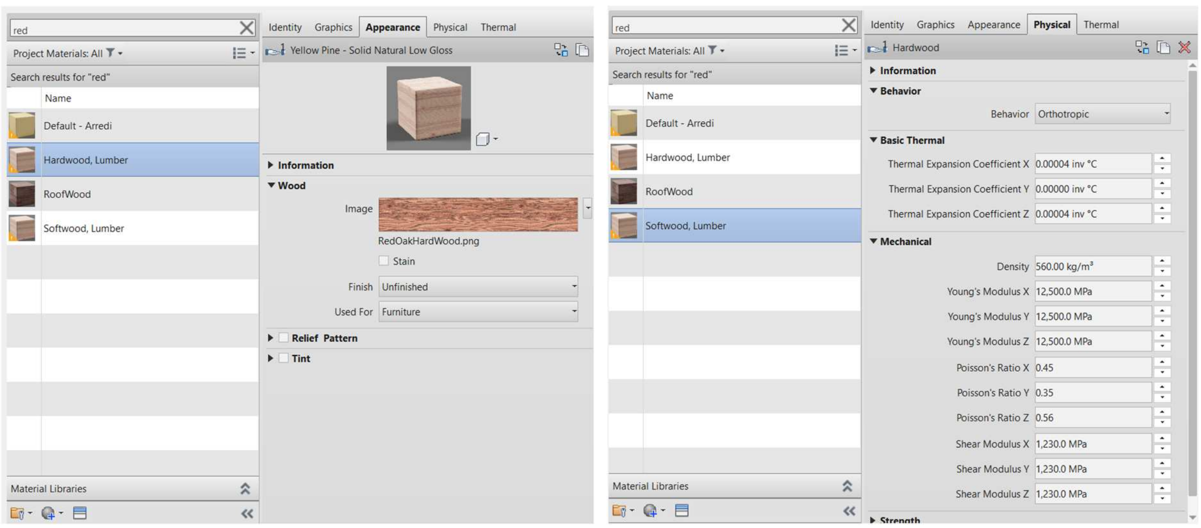

Figure 38 – Material Definition in Revit for the Hardwood Material

All the materials were named according to the uniform naming convention used for the containers, including all the families and their respective types. Moreover, all of the materials were supplied with their mechanical characteristics so that the software could obtain the necessary attributes for structural analysis or facility management throughout the operation and maintenance phase during the exporting process into IFC format.

4.7.5. The Bell Tower

The bell tower is a part of the roof that was created attached to the same model in the lower part of it. The bell tower consists of a wall that is extended from the façade wall and carries a small wooden roof with three hanging bells.

Figure 39 – The Bell Tower in Real life

Figure 40 – The Bell Tower in Revit

The stone slate-covered wooden roof is supported solely by common rafters, which are supported by a ridge beam at the top of the roof and two main frames resting on four wooden brackets at its lower level. The brackets are attached to the brick wall of the tower and act as small cantilevers that hold up the whole system, see Figure 40.

As can be seen in Figure 18 and Figure 39, all the architectural moulding shapes were traced from the point cloud file with the aid of previously acquired field photographs of the structure. In addition to the CAD files already given, see Figure 24.

4.7.6. New Frame Modelling

Figure 41 – New Frames Arrangement on one Side of the Church

All of the frames in the church are considered very old in their assembly. The church was built in the 11th century and renovated twice. However, we considered classifying the frames into two groups: the old frame, which is a single frame at the entrance of the church and considered one of the oldest elements in the church; and the new frames, which are the rest of the frames. These are also old frames but not as old as the frame mentioned previously.

The new frames were positioned over the point cloud model that was linked to the HBIM at an early stage of the modelling process. Using the file's shared coordinates with the structural BIM model, we were able to determine the locations of the frames, which were evenly distributed across the church plane with a centerline spacing of approximately 2.5 metres.

Each of the four sides of the church has a different number of frames; the left transept has one frame with a span of roughly 9.4 metres, while the right transept has one frame with a span of almost 10.4 metres. In contrast, the apse contains three frames with a span of roughly 10.1 metres, while the nave contains four frames with a span of approximately 9.8 metres.

All of these frames were created using the families mentioned in sections (4.7.2.), (4.7.3.) and (A1.4.1.) in Appendix A, using the precise values for each frame's properties. Moreover, these frames were accompanied by steel bracket families that, in reality, link the elements of these frames. See Figure 45.

4.7.7. Old Frame Modelling

Figure 42 – Old Frame Arrangement

At a late stage of the modelling process, the old frame was modelled over the point cloud model linked to the HBIM. The frame is a singular example in which this frame is the only frame in the model. Additionally, it was observed that even when connected to the previous system, Figure 43 shows that the frame in real life was separate from the other frames.

Figure 43 – Separation Between Old (Right) and New Frames (Left)

Due to its proximity to the masonry façade wall that makes up the front of the church, the frame was considered more as a decoration than as a load-bearing frame that supports any loads from the roof as a result of the separation.

For more details about the modelling of this frame, refer to Appendix A – section (A1.5.).

Figure 44 – Old and New Frames Arrangement at the Entrance of the Church

4.7.8. Modelling Detailing

4.7.8.1. Metal Brackets

As the connecting connections serve as the primary places of load transmission, metal brackets are primarily used to stop the lateral movement of the elements and to constrain the elements at these locations, see Figure 45.

Figure 45 – Comparison of the Top Metal Bracket (Laser Scan – Real Life – HBIM)

As there is no specific category for the metal brackets in Revit, we decided to create parametric families with a generic model category, where we can control the width and sometimes the depth of some of these brackets. For more information about the creation of the families, you can refer to Appendix A – section (A1.6.).

There were four main families in the new frame, while the old frame contained only one family. The families were categorised as follows:

- The first one's function is to connect the tie beam and the principle rafter, see Figure 46 and Figure 86.

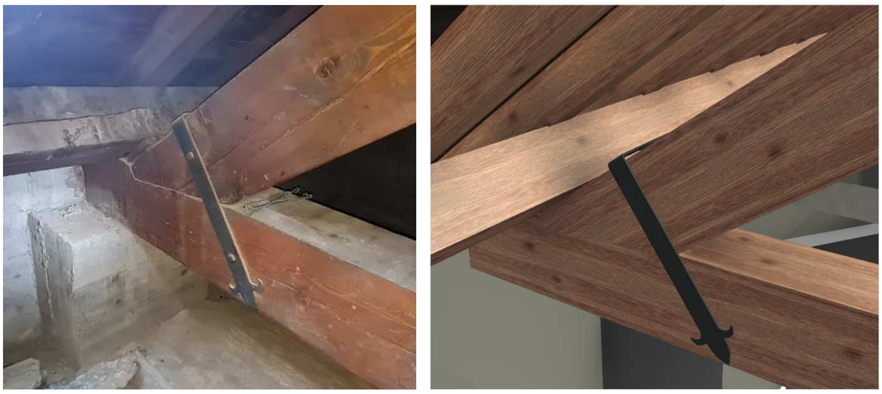

Figure 46 – Metal Bracket Between Tie Beam and Principle Rafter

- The second upper bracket's function is to connect the two principle rafters with the king post, see Figure 47 and Figure 87.

Figure 47 – Metal Bracket Between Principle Rafters and King Post

- The third lower bracket's function is to confine the king post to the tie beam and prevent it from moving laterally, as shown in Figure 48 and Figure 88.

Figure 48 – Metal Bracket to Prevent The Lateral Movement of The King Post

- The final bracket's function is to connect the tie beam parts. As the tie beam is divided into two parts connected to each other through two metal plates at the upper and lower of the section, the two plates are attached to each other by four bolts with four nuts. The main function of this plate is to convert the axial loads applied over the tie beam to and transferred from the roof loads, as shown in Figure 49 and Figure 89.

Figure 49 –Metal Plates in the New Frame

- The old frame has just one family that is preventing the main web from lateral movements. The bracket seems to be so old and reused during the first intervention, as shown in Figure 50 and Figure 90.

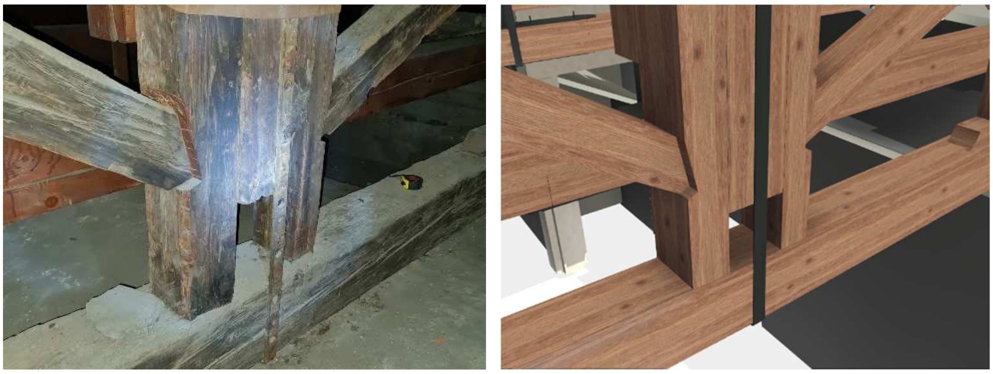

Figure 50 –Metal Brackets in the Old Frame

4.7.8.2. Wooden Connections

Prior to commencing the modelling process, a site visit was made to measure actual dimensions from the site. A measuring tape was used to record the measurements in a notebook, and small sketches were drawn to ease the process of transferring the data afterwards in the digitalisation process, see Figure 51.

In addition to that, several resources were checked for the accuracy of these woodwork connections. One of these sources was the “Tetti” book or Roofs by “G.A. Breymann”. The book offered several data about the connections (Breymann, 2003) and the “Manuale Pratico del Carpentiere in Legno” by “P. Pogliano”, which offered the craftsmanship used in making these connections in real life, with extensive details, see Figure 52.

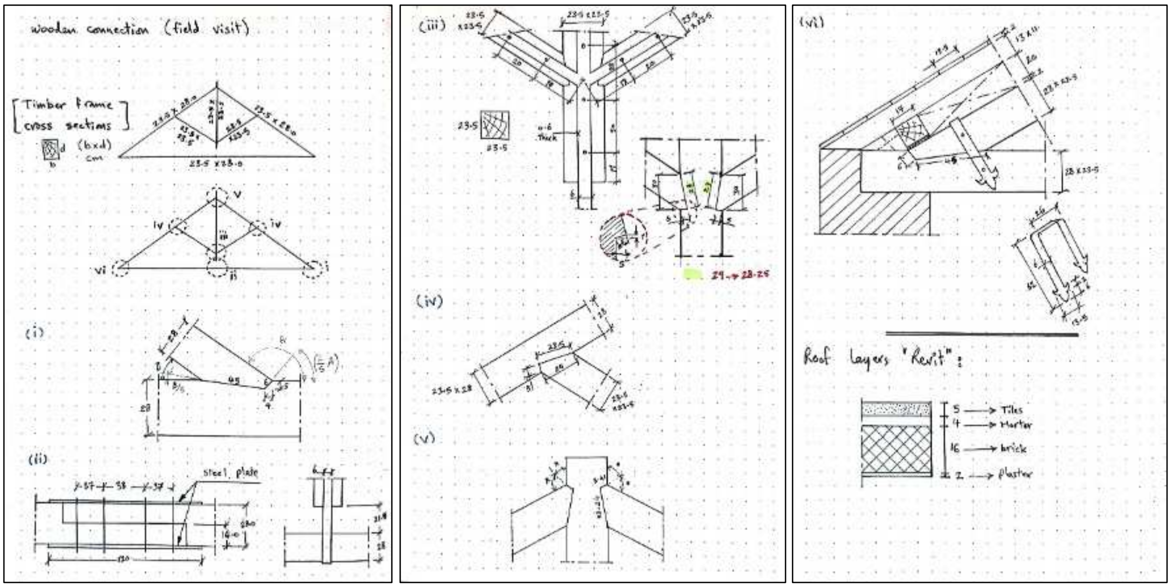

Figure 51 – Field Visit Tape Measuring for the Wooden Connections

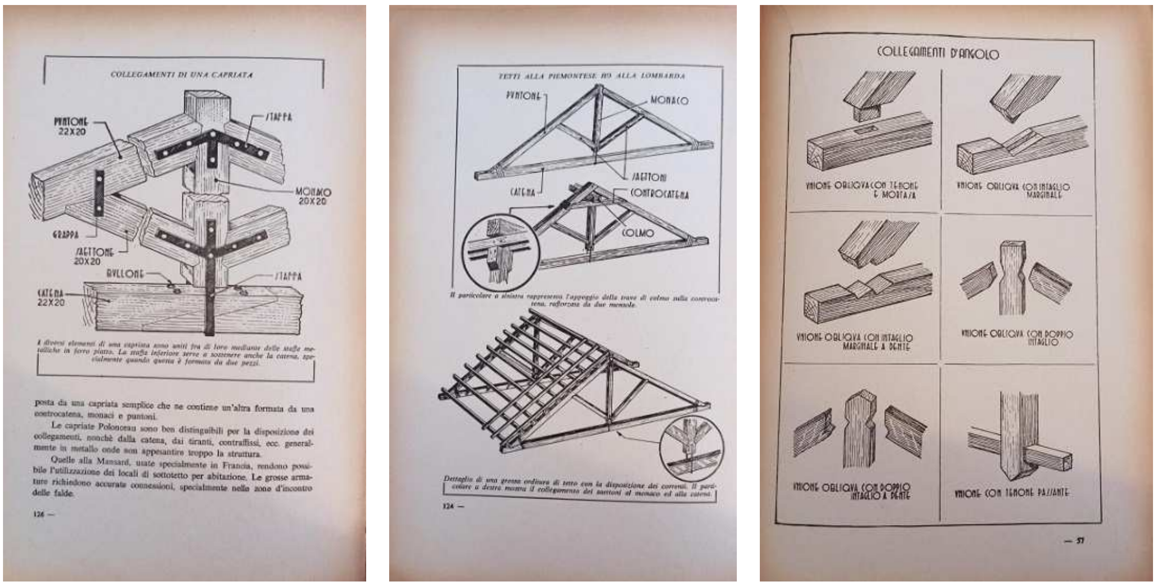

Figure 52 – Woodwork Details [Source: (Pogliano, 1960)]

The obtained data were compared with the references data to ensure using the same modules and ratios, as most of the connections were dismantled due to the old constructions, considering that facilitated the wooden details modelling.

4.7.8.3. Modelling The Roof Layers

In addition to the measurements for the wooden connections and cross-sections, it was noted that the roof is consisting of several layers. As was noticed from the skylight window in the left transept that there are three layers of wood, the first of which was fixed directly to the common rafters. The second and third layers are arranged perpendicularly to the first layer and serve to protect it from severe deflection, see Figure 53.

Figure 53 – Roof Layers Measured on Site

Consequently, these layers were identified inside the Revit file, by adjusting the roof with three layers of softwood, and one layer of stone slate tiling to mimic the real-life floor, see Figure 54.

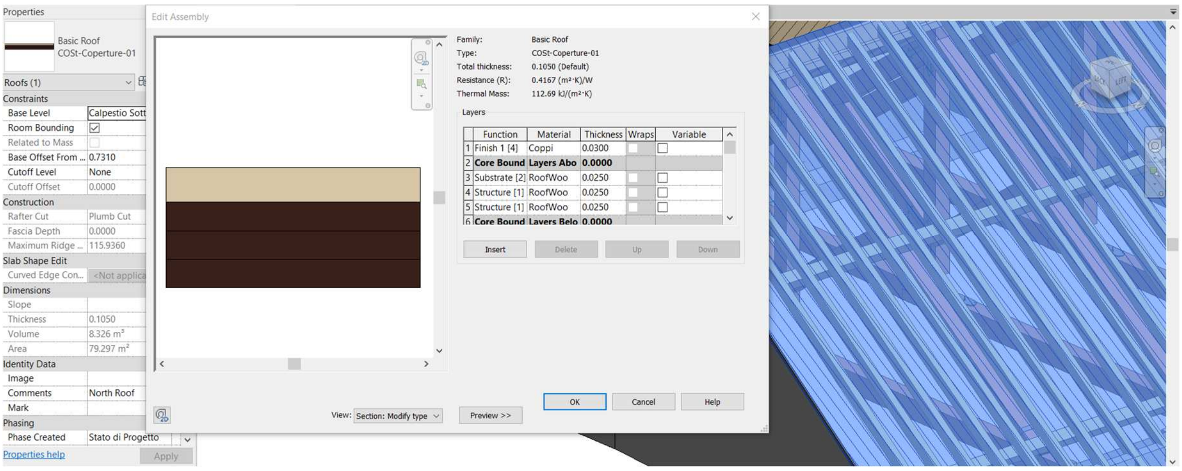

Figure 54 – Roof Layers in Revit

4.7.8.4. Extra Features and Details of the Model

The HBIM model needed to have a few details taken care of. To start, some rafter tails were sculpted at the ends of the extensions of the purlins of the old frame in the façade wall to give the wooden elements in the HBIM a finishing touch. In order to replicate the same size and form for each frame element throughout the modelling process, the shape was traced from the point cloud file, as shown in Figure 55.

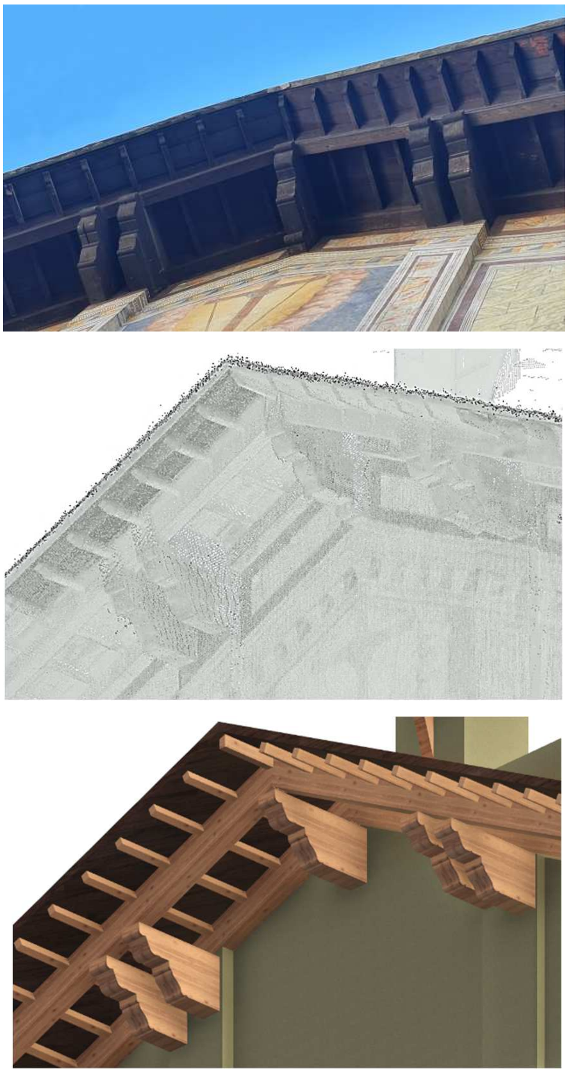

Figure 55 – Comparison of the Wooden Rafter Tails (Laser Scan – Real Life - HBIM)

We used a basic Revit family to model the doors that provided access to the external roof of the apse and transept on the exterior walls that carry the roof in the other portions of the church, see Figure 56.

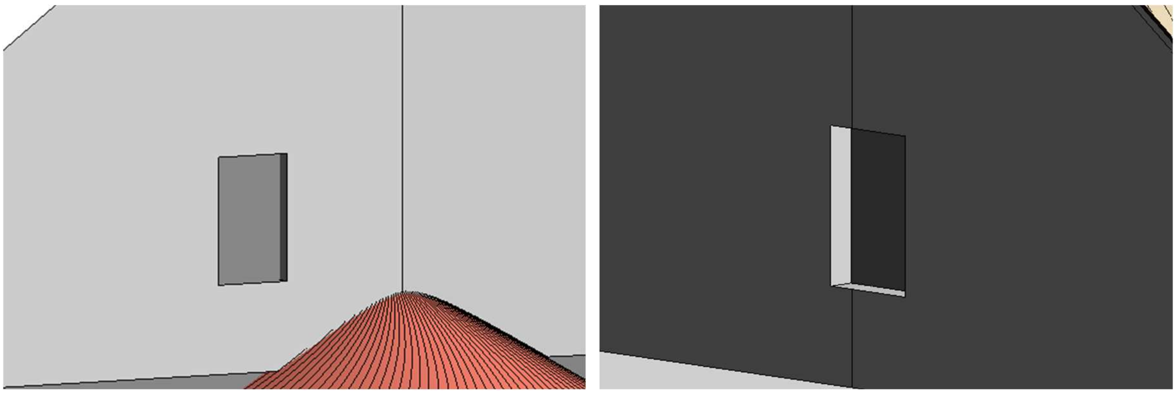

Figure 56 – Doors in the External Walls

Similarly, the same technique was used for the windows and skylight, as there was one skylight on the roof of the left transept, the family was adjusted with the same dimensions as the real one and matched the dimensions in the point cloud, see Figure 57.

Figure 57 – Skylight in the Left Transept Roof

Finally, the walls that carry the dome in the middle are encasing the four roofs from the dome side in the middle, these walls were modelled to control their height at the top level of the roof, and to coordinate the openings that are shown in Figure 58.

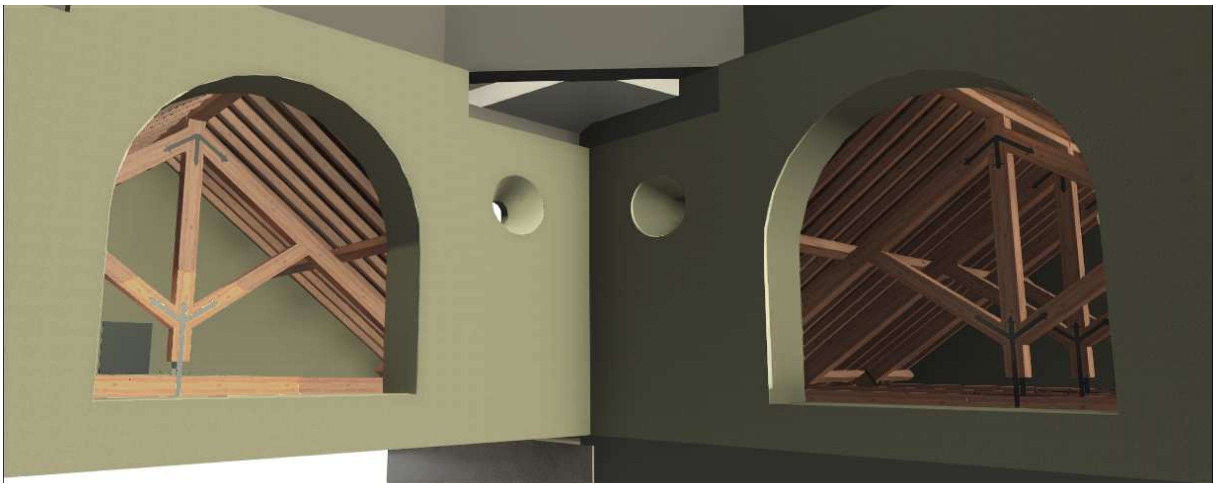

Figure 58 – Wall Openings

5. STRUCTURAL ANALYSIS OF THE SYSTEM

5.1. MATERIAL TYPE IDENTIFICATION

One of the key elements in historical preservation is the identification of the used materials. This is needed not only for repairing or replacing the heritage with the same materials as the original but also for scientifically documenting the heritage and taking any preservation-related actions (Timar, et al., 2012). We can obtain a type of material by several means; from the most accurate ways to estimate the type by some investigation and geographic growth of natural resources.

5.1.1. Physical Appearance

This procedure often takes place through observation and physical contact with the substance. For instance, if the material is wood, we must first confirm that it is wood and not another similar material, such as composites. You can do this by examining the end-grain and the growth rings created by a tree's yearly development (Meier, 2008). The wood's colour, which ranges from pale cream to yellowish-brown, is another factor. Each species has a distinctive colour that sets it apart from the other species; experts in wood and other highly skilled individuals in this subject can typically identify this characteristic (Hardwood Distributors Association, 2022). One of the most important aspects of determining the species is looking at the wood grain. Grain-related factors need to be taken into account, including wood texture, sawing method (quartersawn vs. plainsawn), and unique features like sapwood, curly or wild grain, burls/knots, etc. (Meier, 2008).

5.1.2. Experimental Methods

This method requires some samples from the material, by locating some less deteriorated parts displaying longitudinal and transversal sections in the grain arrangement for a macroscopic examination of the anatomical features of the material, By comparing the material to several relevant materials, this approach can determine the material's kind and reveal its molecular structure. A microscopic technique, on the other hand, can give a more accurate assessment if a macroscopic one isn't clear, either because some species look alike or due to the occurrence of degradation phenomena (Timar, et al., 2012), see Figure 59.

5.1.3. Estimation Based on Evidence

This approach is the least reliable since material assessment requires very strong evidence as well as detailed knowledge of the place's history, geographic factors, and the common materials used in the historical era where the heritage was constructed. If the material was supplied locally, such as from mines or neighbouring forests, where every component was crafted from locally grown trees, the number of available species is immediately constrained. However, the material utilised for heritage tends to use specific types based on the year of building, making a rational estimate much easier (Meier, 2008).

In the following section of this chapter, we will use this approach to identify the material used in the construction of the church's roof, and as a result, we will obtain the loads resulting from this assumption. Due to the time constraints of the execution, this approach will be used in this case study.

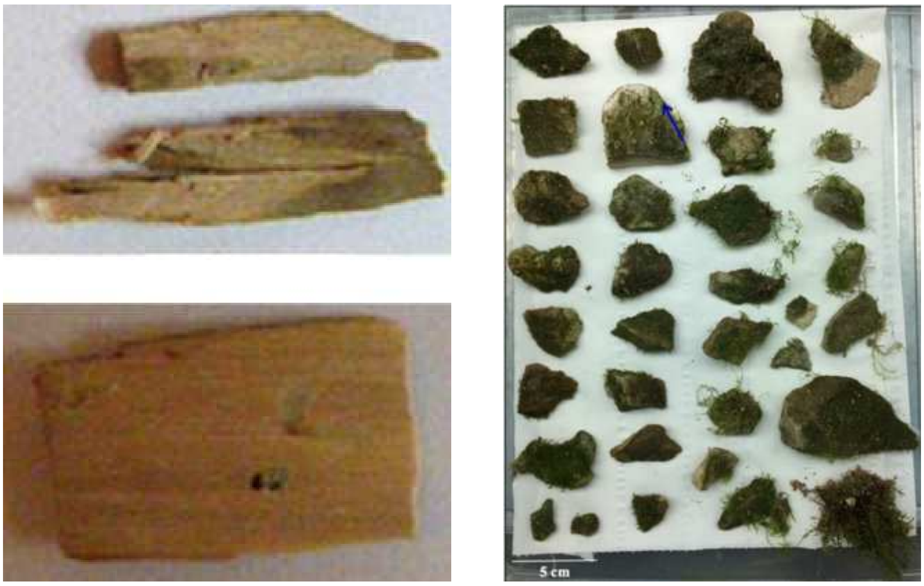

Figure 59 – Material Sampling for Macroscopic Examination [Sources: (Timar, et al., 2012) (Pfendler, et al., 2021)]

5.2. SUBJECTED LOADS CALCULATION

5.2.1. Permanent Loads

The permanent loads include the weights of the wooden elements of the roof (main trusses, common rafters, purlins, and the ridge beam) as well as the covering slates loads. This section will be divided into three major categories: hardwood, softwood, and stone slates.

As a disclaimer, I would like to clarify that this part of the study is intended to serve as a guide for the procedure of evaluating the safety of a heritage's cross sections. As a result, we won't design every section and every frame of the roof; instead, we'll focus on just one frame analysis, load calculations, and cross-section safety checks, leaving room for future study or the application of this method in businesses.

The selected frame is going to be frame number 01 as shown in Figure 60, based on the large contributory area that the frame is serving for the active loads, the length of this area was calculated to be 2.835 meters, and it serves from both the centerlines of the adjacent areas in front and behind the frame.

5.2.1.1. Main Frame (Hardwood)

The estimation of loads requires knowledge of the material being used for construction. Due to the lack of information concerning this matter, we can only obtain the type of material by the third method mentioned previously, which is to investigate the geographic growth of natural resources. Como is located on the north side of Italy where the closest forest is located in the "Vigezzo Valley in Piedmont". The forest lies between Lake Maggiore and the Swiss Alps and is considered a huge source of hardwood like oaks, maples, beeches, and chestnut trees, with a variety of softwood like firs and larches (Idealista, 2021).

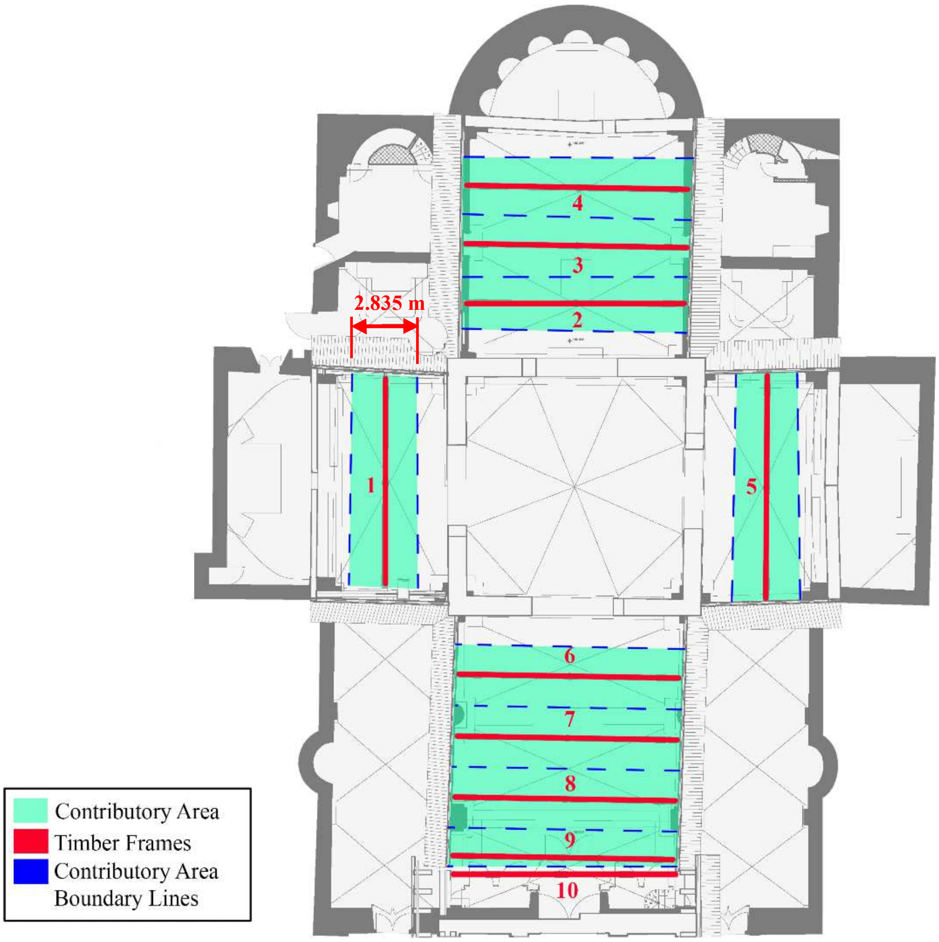

Figure 60 – Plan View of Contributory Areas of Loading Strips Over Frames

Research shows that numerous oak species predominate in the most common forest forms in Italy (Maselli, et al., 2010). So, as a close estimation, we will consider the main trusses to be made out of red oak, and as a result of the estimation, we can extract the mechanical characteristics of the material, which will help us analyse the loads, design the sections, and check their safety against the existing loads.

All the necessary data required for each wood type is summarised in Table 2 (United States Department of Agriculture, 2010).

As a common use for the HBIM, all the required information for the design and the load analysis can be obtained from the model. Using the proprietary file generated from Revit, it was easy to get the total weight of the model elements. By adding a simple equation to multiply the volume by the material density, I obtained the weight of each frame of the king post frames. Figure 61 shows how the schedule was generated in Revit. You can find the summarised table of weights for all the frames in Table 3 – Appendix B.

As a result of studying just one frame, as mentioned previously, the weight that was calculated after choosing the first frame was 1415.167 kg. We shall see why the first frame was chosen in the following section when we compute the weight of the roof, as it bears the highest loading span among the other frames.

<King Post Frame Weight>

A	B	C	D	E	F
Type	Length	Volume	Wood Density	Comments	Weight
					10473.700405
Frame 01					
23.5x23.5	3.5700	0.1850 m³	790	Frame 01	146.151413
23.5x23.5	2.2837	0.1130 m³	790	Frame 01	89.259324
23.5x23.5	2.2237	0.1098 m³	790	Frame 01	86.75805
23.5x28.0	5.1654	0.3356 m³	790	Frame 01	265.101937
23.5x28.0	5.8862	0.3653 m³	790	Frame 01	288.586617
23.5x28.0	4.6453	0.3174 m³	790	Frame 01	250.72767
23.5x28.0	5.8890	0.3653 m³	790	Frame 01	288.582316
					1415.167327
Frame 02					
23.5x23.5	3.5900	0.1861 m³	790	Frame 02	147.013507
23.5x23.5	2.3790	0.1183 m³	790	Frame 02	93.449247
23.5x23.5	2.3755	0.1181 m³	790	Frame 02	93.279654
23.5x28.0	5.4860	0.3583 m³	790	Frame 02	283.023301
23.5x28.0	6.1800	0.3841 m³	790	Frame 02	303.406099
23.5x28.0	5.0440	0.3466 m³	790	Frame 02	273.839342
23.5x28.0	6.1900	0.3847 m³	790	Frame 02	303.899887
					1497.911038
Frame 03					
23.5x23.5	3.6000	0.1877 m³	790	Frame 03	148.267881
23.5x23.5	2.3424	0.1186 m³	790	Frame 03	93.671432
23.5x23.5	2.3956	0.1172 m³	790	Frame 03	92.575243
23.5x28.0	5.4256	0.3475 m³	790	Frame 03	274.555216
23.5x28.0	6.1060	0.3828 m³	790	Frame 03	302.438102
23.5x28.0	5.0601	0.3439 m³	790	Frame 03	271.689747
23.5x28.0	6.2129	0.3840 m³	790	Frame 03	303.341849
					1486.53947
Frame 04					
23.5x23.5	3.6000	0.1863 m³	790	Frame 04	147.138438
23.5x23.5	2.3464	0.1188 m³	790	Frame 04	93.857805
23.5x23.5	2.4001	0.1174 m³	790	Frame 04	92.770812
23.5x28.0	5.4654	0.3634 m³	790	Frame 04	287.05281
23.5x28.0	6.1472	0.3854 m³	790	Frame 04	304.451041
23.5x28.0	5.1000	0.3653 m³	790	Frame 04	288.597482
23.5x28.0	6.2542	0.3865 m³	790	Frame 04	305.353725
					1519.222112
Frame 05					
23.5x23.5	2.3779	0.1174 m³	790	Frame 05	92.759345
23.5x23.5	3.5400	0.1821 m³	790	Frame 05	143.832589
23.5x23.5	2.3649	0.1181 m³	790	Frame 05	93.335384
23.5x28.0	5.6247	0.3560 m³	790	Frame 05	281.265619
23.5x28.0	5.2301	0.3585 m³	790	Frame 05	283.199265
23.5x28.0	6.3323	0.3918 m³	790	Frame 05	309.489142
23.5x28.0	6.2868	0.3908 m³	790	Frame 05	308.706567
					1512.58791
Frame 06					
23.5x23.5	3.5800	0.1856 m³	790	Frame 06	146.653755
23.5x23.5	2.2898	0.1135 m³	790	Frame 06	89.700752
23.5x23.5	2.3166	0.1148 m³	790	Frame 06	90.685966
23.5x28.0	4.8750	0.3437 m³	790	Frame 06	271.557535
23.5x28.0	6.0424	0.3750 m³	790	Frame 06	296.237797
23.5x28.0	4.9401	0.3467 m³	790	Frame 06	273.867755
23.5x28.0	6.0774	0.3775 m³	790	Frame 06	298.238852
					1466.942412

Figure 61 – Schedule of Material Take-off generated by Revit

5.2.1.2. Rafters (Softwood)

By adopting the same strategy and accounting for the same wood source, the same forest in "Vigezzo Valley in Piedmont". The closest guess for the softwood components was that they were made of larch. Similar to this, we may draw out the mechanical properties of the material to aid in load analysis, section design, and safety testing against current own weights.

The main softwood elements can be itemised to be as follows: the common rafters, purlins, and the ridge beam, which is located on the apex of the truss frame to connect their top ends.

All the mechanical properties of Larch were mentioned in Table 2 as well, and these characteristics are beneficial during the study of the stresses because they assist the sections in mimicking the behaviour of the actual sections in real life, improving the accuracy of the results.

Table 2 – Material Mechanical Properties

	Red Oak	Larch	Serpentine
Young's Modulus (MPa)[1]	12500	12900	76400
Poisson's ratio[2]	0.35	0.355	0.35
Coefficient of Thermal Expansion (µm/m-°C)[3]	4.90	4.90	1.43×10^{-6}
Weight per unit volume (kg/m^3)	790	550	2600

5.2.1.3. Stone Slates

Using the same technique we applied to the timber elements. The stone slates were assumed to be serpentine. The hypothesis was supported in research by Alessandro Cavallo (2022), who stated that serpentine was widely used in northern Italian territories in the eleventh century. Evidence for this use was discovered just above the village of San Giuseppe in Valmalenco, where there is a natural ridge, and the serpentinite is particularly schistose. "Testing" those stony banks that readily split into slabs to cover the roofs didn't cost much for the local craftsmen who were already professionals in the mining of the nearby iron mines, Figure 62.

Figure 62 – Roof Slab Covering in Valtellina and typical rural houses in San Giuseppe village, Valmalenco (Cavallo, 2022)

This assumption can help in determining the weight per unit volume of 2600 kg/m3 by visually comparing the colour and shape of these slates and based on the fact that the material is acceptable for usage as a roof covering material (Fumagalli & Klemme, 2015). As shown in Figure 18 and Figure 63, there is a resemblance between these roofs and the roof of the church.

[1] For the timber, it was assumed that it has a 12% moisture content.

[2] For the timber, we will take the μ_{LR} value which denotes the ratio for stress along the longitudinal axis and strain along the radial axis.

[3] For the timber, At a temperature of 20.0 °C - Typical value for Oak and Larch in the Axial direction.

Figure 63 – Roof Slab Covering in Chiesa Di San Gaicomo

5.2.2. Snow Loads

The climate of Italy is generally the Mediterranean, with hot summers and abundant rainfall, but the region also features several climatic changes with weather conditions that differ from the typical Mediterranean climate. During November and December, the Alpine areas are blanketed in a thick blanket of snow. Moreover, cities such as Como, Milan, and Florence aren't an exception (Travelperi, 2022).

The Eurocode EN 1991-1-3:2003 regulations are made to ensure that the snow loads are adequately calculated during the design of a new building or to check the safety of the design in existing buildings. As a result, the European code has regulations for taking the snow loads into account when designing the imposed loads over a building in the northern territories. Since the snow loads must have changed over the previous 600 years owing to global warming and the exposure factor of the structure to the snow load due to the spread of civilization, our use of the code will be limited in this situation since we have a heritage building. However, in our case study, we will use the code requirements as a guideline to determine if the building's outdated design can support the loads that may be predicted in the present day.

5.3. BOUNDARY CONDITIONS AND ANALYSIS

The locations on the truss where the external force or displacement is known at the beginning of the analysis are known as the boundary conditions. Usually, these locations are both the left and right supports. In our case, we can assume that the truss is stable over two-pin supports.

Given that all of the support reactions and member forces of the truss can be calculated using simply the equations of static equilibrium, it will be assumed that the truss is statically determinate. Additionally, the equation for statical determinacy can be calculated with the following Equation (1);

$$b + r = 2j \qquad (1)$$

Where;

b	is the number of truss members.
r	the number of support reactions.
j	the number of joints

As shown in Figure 64, the truss has 8 members, 6 joints, and 4 support reactions. Hence $8 + 3 \leq (2)(6)$, the truss is statically determinate.

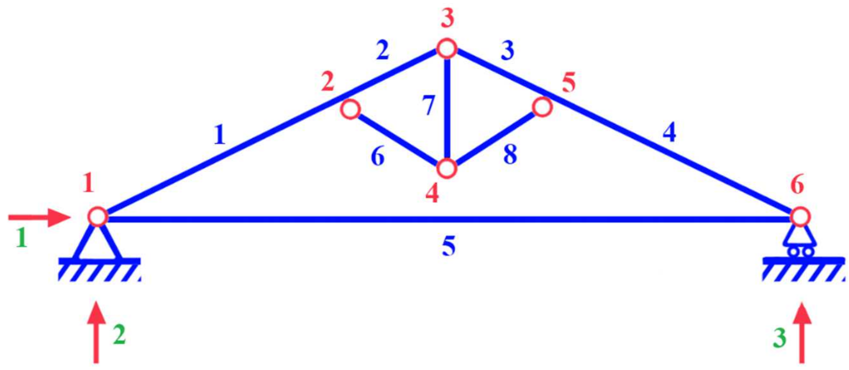

Figure 64 – Statically Determinate Truss

By identifying the supports, it is possible to analyse the truss against its permanent loads, calculate the reactions at the supports' positions in addition to the axial forces carried in its members, and define the force's magnitude and type. In the subsequent section of the research, the Figure 65 workflow will be implemented.

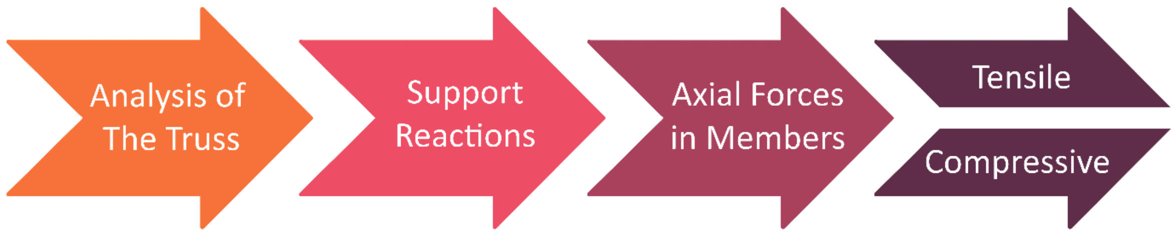

Figure 65 – Truss Analysis Workflow

5.3.1. Analysis of Permanent Loads

Loads of the main frame, the purlins, common rafters, principal rafters, ridge beam, and the stone slates are where the permanent loads affecting the frames are collected. To determine the straining actions acting over the frames, all of these permanent loads were taken from the Revit model and then adjusted using manual and computerised calculations. For the complete truss load computations, refer to Appendix B.

These permanent loads are the sum of the weights of the hardwood, softwood, and stone slates, as indicated in Figure 66. The distributed loads represent the frame's own weight (Hardwood), whereas the point loads indicate the concentrated loads over the purlins transferred from the Roof components (Softwood and stone slates).

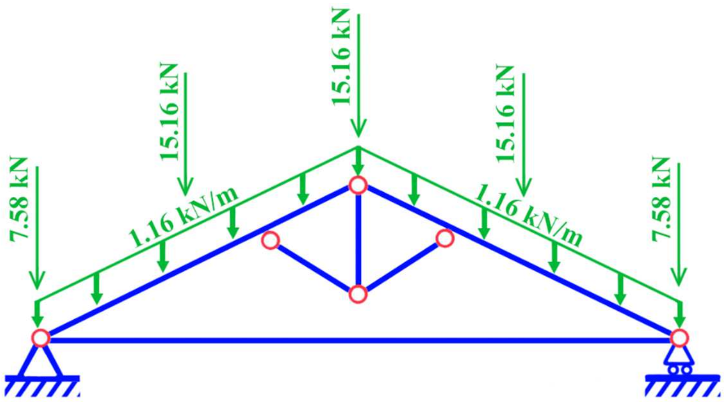

Figure 66 – Truss Total Permanent Loads

5.3.2. Analysis of Snow Loads

The snow load is estimated using Eurocode code (EN 1991-1-3, 2003) equation (5.1), which may be found in Appendix B - section (B1.2.) along with the entire calculation method. The snow load is a combination of parameters that affect the amount of the load; these parameters are dependent on the load shape of the snow, which is dependent on the roof inclination, which can also affect the roof's exposure to the snow load, as well as the building's location in its region and the geography of that region.

Another factor is the coefficient of thermal losses within the building, since each building has its own thermal emissions that cause snow to melt over time, and the load may be determined based on its features at ground level.

The total snow loads were determined based on Italy's location in Zone 2 of the national annexe, and the load value is 0.185 kN/m2. As seen in Figure 67, and similarly to the roof's permanent load transfer behaviour, the load transmitted from the Roof components is concentrated over the purlins.

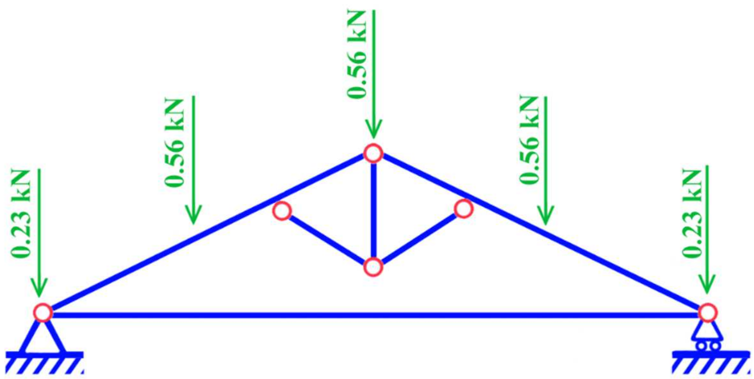

Figure 67 – Truss Total Snow Loads

5.3.3. Using SAP2000 to Analyse Loads and Load Combinations

To obtain the straining actions, all the calculations were done using SAP2000 software, by modelling one frame inside the software, applying all the loads to its locations, adjusting the members' releases, and defining the boundary conditions. The same technique was followed in research to analyse the timber roof loads of the Aula Magna of the university of Pavia, in Pavia, Italy (Morandotti, et al., 2017).

To start with this analysis, we need to generate a geometry inside the software first. The software allows integration with Revit through an add-in created by CSI company, the software vendor, the tool is known as “CSiXRevit”, in this study we used SAP2000 version 24 as the latest version of the software, and we found a compatible version of the tool. A separate Revit file was prepared to contain just one frame, so we can export the analytical model. Prior to the export phase, I needed to adjust the analytical model as the model was realistic in its orientations and locations of the elements, so I had to adjust the analytical model to be in an ideal shape for the analysis and to make it easier to adjust any deformations or settlement inside SAP2000 software, see Figure 68.

The software allows one to make a grid for defining the outline geometry of the structure of the study, then all the frames need to be defined, and modelled to their location, and assigning cross section dimensions for them. By calculating the permanent and the imposed loads, a load combination was assembled to study the effect of these existing loads on the existing frames and to check their safety using the Eurocode limits states.

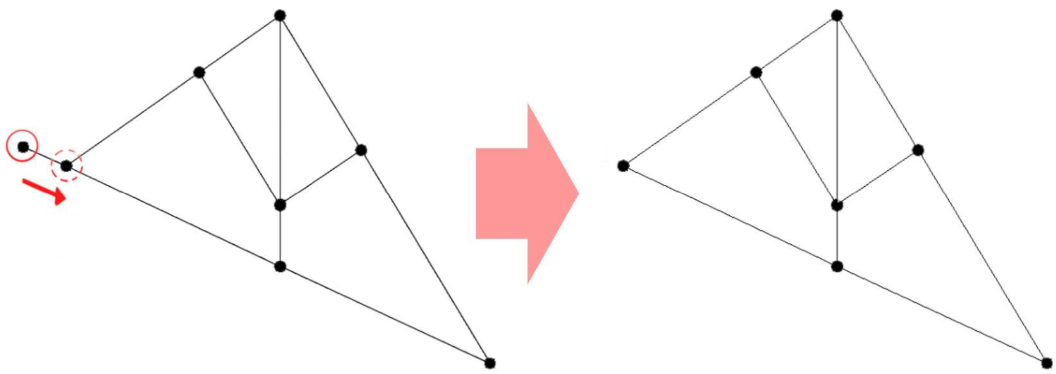

Figure 68 – Analytical Model Adjust in Revit

In this study, we used the Ultimate limit states load combinations, as these limit states are concerned about the safety of both the people and the structure as well (EN 1990:2002+A1:2005, 2005).

By analysing the loads over the existing geometries, the final results for the axial loads, and moments over the truss can be found in the summarised Table 4 in Appendix B.

5.4. DESIGN OF THE SECTIONS AND CHECK SAFETY

By having all the obtained results in the previous steps, we can start designing the cross-sections according to Eurocode 5 which is concerned with designing timber structures (EN 1995-1-1:2004+A1:2008, 2008). The design can be automated using other software or manually similarly to the previous procedures.

A practical example of software that can make the design of the frame according to the Eurocode 5, a software called “WOODexpress”, the software is developed by “RUNET software & expert systems”. The software can design the wooden sections, in addition, it can design the wooden connections with its metal brackets (RUNET, 2020), see Figure 69.

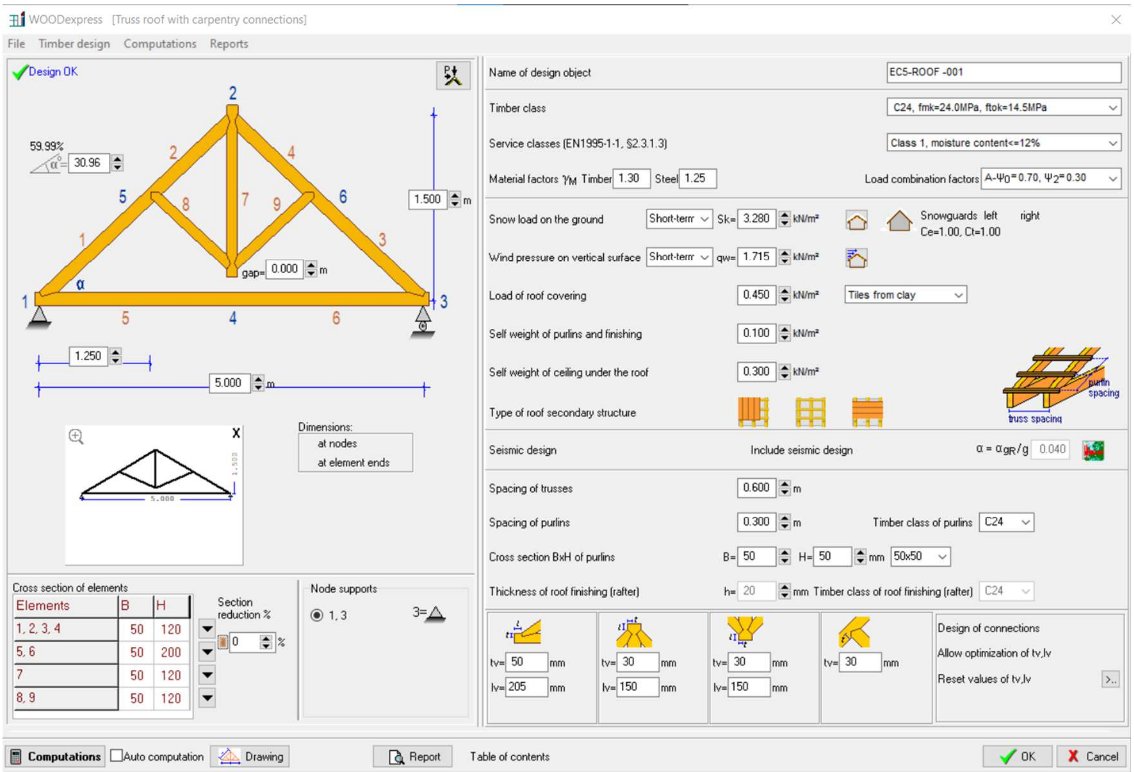

Figure 69 – WOODexpress Software

The designed section will indicate that these dimensions are suitable for the frame and its subjected loads, in the meantime, a comparison between the existing and the new design sections. This comparison allows the designer to check the safety of these sections, and define the appropriate intervention required for each member according to the loads subjected on the frame.

The whole procedure behind this check can be adjusted according to the type of the frame, the subjected loads, and the severity of the deterioration in the existing cross-sections. Besides, the design codes can change according to the construction material, in our case it was a timber structure which allowed us to use Eurocode 5, in other projects we may encounter steel frames or any similar material that will allow us to use its corresponding design code.

6. CONCLUSION AND MAINTENANCE PLAN

Within the confines of this thesis, we were able to create a three-dimensional HBIM that has the potential to function as a digital twin for a number of different applications. We computed the loads that were being imposed on the roof, evaluated those loads to the cross sections that were already there, and then generated all of the geometries necessary for the scope of our work using the parametric library that was already built into the model. The approach was simple but time-consuming because it required several iterations of the modelling procedure in order to obtain a robust model that could be utilised in a variety of contexts.

The model was used to calculate precise volumes for the timber and stone components of the roof. The model may also produce a bill of quantities if necessary because all the information about the wood structure was included in the element's metadata. To correctly replicate the real material used for the building and to display the right rendering pictures, the material was provided for each element, which may also help with managing the model in the future for maintenance requirements and operation.

The material evaluation that we did serve as the basis for the computation of the expected loads that would be placed on the roof. If you want more accurate results, we recommend conducting a microscopic study of the specimens. For the purpose of the load study, only the permanent loads, in addition to the snow loads, were considered. For a more accurate depiction of the loads, it is recommended that other imposed loads, such as wind and seismic loads, be included in the analysis. Regarding the safety of the cross-section, we recommend utilising the finite element method to analyse the loads that are distributed across the frames for greater accuracy. Additionally, we recommend conducting safety checks on the wooden sections by adhering to the guidelines provided by Eurocode.

In a nutshell, we described a workflow for ensuring the safety of cultural heritage. This workflow is straightforward and well-organized for any organisation that cares about protecting cultural heritage, and it can help in documenting the thematic data of heritage in a digital format, including both geometric and alphabetical forms. There are countless uses for this procedure and the resulting model, and we may add more components to it to broaden its use or even more information to meet the project's increased information needs.

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LIST OF ACRONYMS AND ABBREVIATIONS

The following table describes the significance of various abbreviations and acronyms used throughout the thesis:

AIR	Asset Information Requirement
AIM	Asset Information Model
BEP	BIM Execution Plan
BIM	Building Information Modelling
CDE	Common Data Environment
CRM	Conservation, Repair, and Maintenance
EIR	Exchange Information Requirements
HBIM	Historic/Heritage Building Information Modelling/Model
IFC	Industry Foundation Class
LOD	Level of Detailing/Development
OIR	Organisational Information Requirement
PIM	Project Information Model
PIR	Project Information Requirement
SAP	Structural Analysis Programme

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APPENDIX A: MODELLING ITERATIONS

A1.1. MODELLING THE FRAMES

Modelling the church frames was challenging in many ways, knowing that the structure is more than 600 years old, the severity of the elements' distortions caused by the humidity of the atmosphere inside the church, and the inaccessibility of the roof to gather information about the dimensions of the trusses, and the lack of light in the roof area, which made it difficult to get clear photos. All these challenges were mitigated in part by creating a point cloud model. However, manipulating the model was difficult, and the roof below the trusses was uneven, making it difficult to perform many point cloud attempts over it. In the following section, we will go over how the modelling procedure trials were carried out in Revit, including steps for the approaches and techniques used.

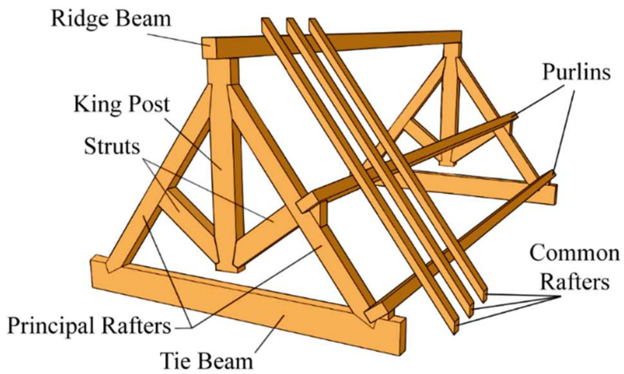

Figure 70 – The Relation between the Roof's Elements

A1.2. FIRST TRIAL

A1.2.1. Modelling Process of the First Trial

By creating a parametric family for the "King Post Truss" inside Revit software, the family consisted of the truss's main statical lines and two main parameters to control the truss's length (TrussLength) and height (TrussHeight), as shown in Figure 71:

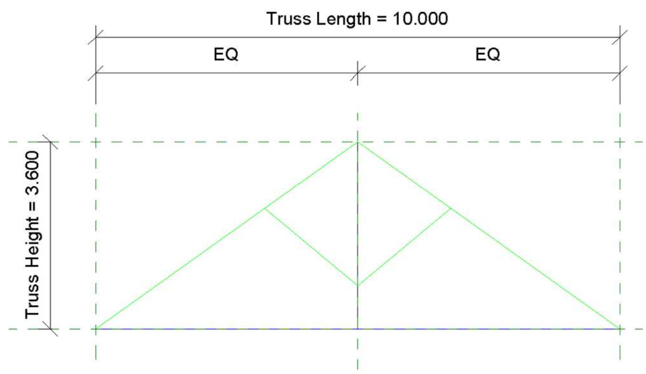

Figure 71 – Main Truss Revit Family Outlines

Loading the family inside the project causes it to behave similarly to any structural frame family; we must select the start and endpoints of the frame location on the plan, then assign all the frame sections to each member of the truss's lower chord, struts, and rafters. As illustrated in Figure 72.

The final shape will differ slightly from the original arrangement after adjusting the ends of all the wooden cross-sections along the truss, with some protrusions for some members.

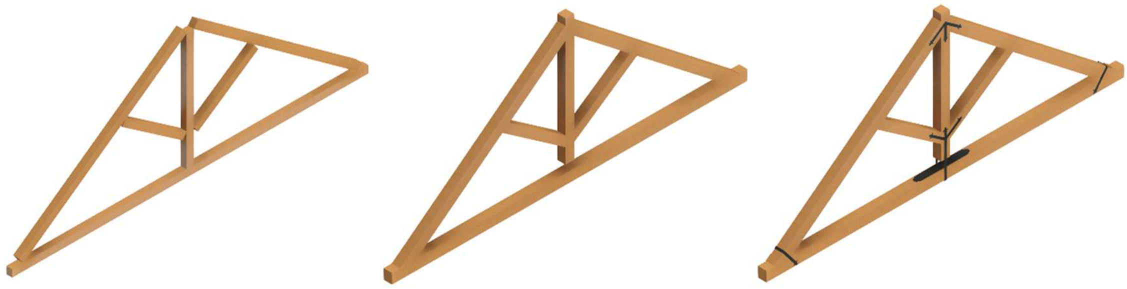

Figure 72 – Assigned and Adjusting Frames of the Truss

A1.2.2. Results and Conclusion of the First Trial

Except for the old N-Truss, which required a different modelling approach, the family was modelled on the plan for the locations of all the trusses.

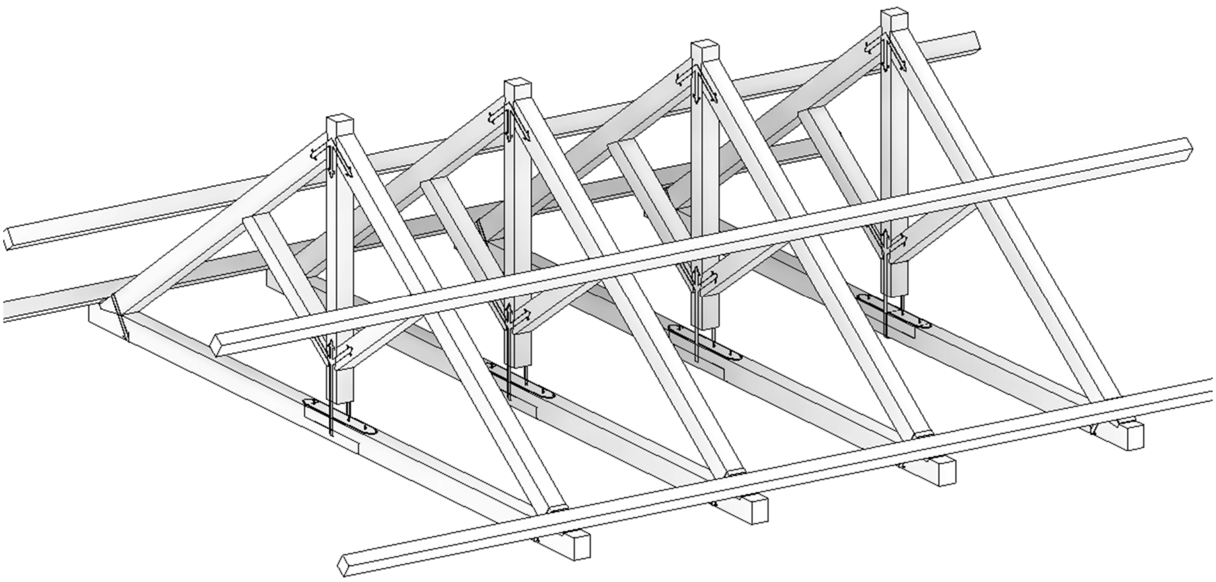

Figure 73 – Using the Truss Family for the Typical Frames

From a distance, the finished product for this family appeared to be adequate, as shown in Figure 73. However, it was unsatisfactory on a micro level because the real-life frames were severely distorted, and the family was designed for non-deformed frames, making it impossible to adjust the frame at the support location and adjust the inclinations and cross-section rotations. The frames (wooden colour) were not aligned over the point cloud locations, as shown in Figure 74. (Red-coloured).

In addition to that, the angle between the "Struts" and the "king post" was fixed and wasn't matching the real angle, which required an adjustment to the family to control it.

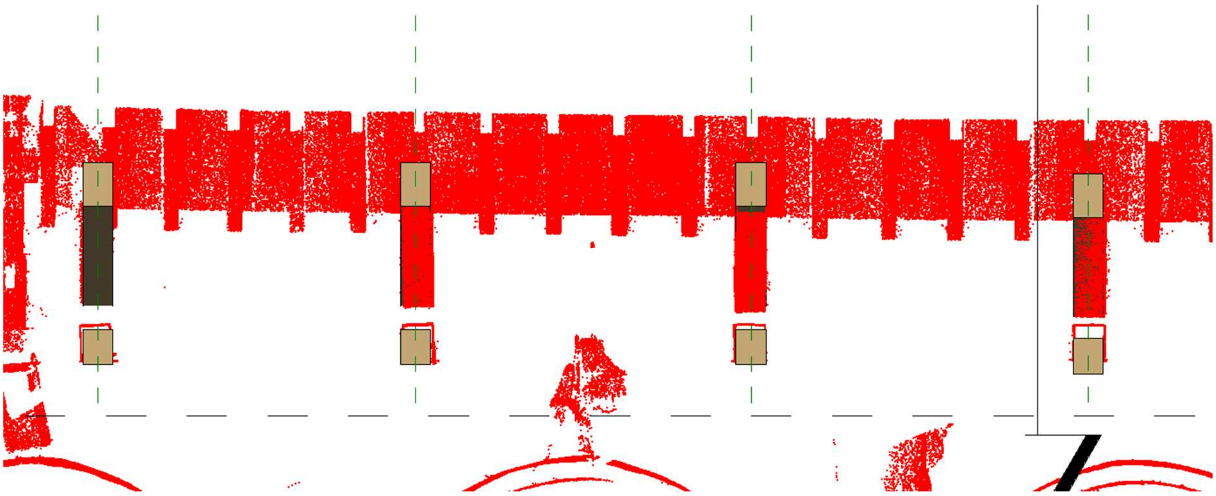

Figure 74 – Locating the Wooden Frames Over the Point Cloud File

A1.3. SECOND TRIAL

A1.3.1. Modelling Process of the Second Trial

Similarly to the previous family, an adjusted family was created to control the same parameters in addition to the angle between the "struts" and the "king post". The family consisted of the main statical lines of the truss with the same two main parameters to control the length of the truss "TrussLength" and the height of the truss "TrussHeight", in addition to two parameters to control the Angles "A1" and "A2", as shown in Figure 75:

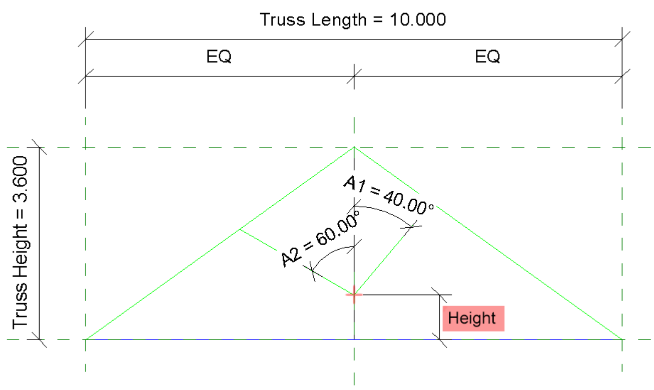

Figure 75 – Second Truss Revit Family Outlines

A1.3.2. Results and Conclusion of the Second Trial

The family was flexible, like its predecessor, however, there was an over constrain in the elevation of the right and left ends of the family, in addition, when the angle between the "Struts" and the "king post" changed, the length of the whole truss was affected, see Figure 76, which was amended by adding more constraints between the principal rafters and the endpoints of the struts, in addition to another constraint to the endpoints of the principal rafters to the truss length reference planes. That adjusted the length deformation, but it didn't solve the truss endpoint height, in addition to the mid-joint height, see Figure 77. This observation opened a new possibility to reengineer the whole family from scratch and led to some suggestions to follow a new way of creating the family and to add extra points to adjust the height, length, and angle.

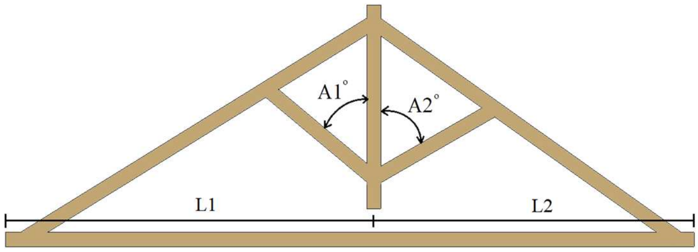

Figure 76 – Assigned and Adjusting Frames of the Truss for the New Family

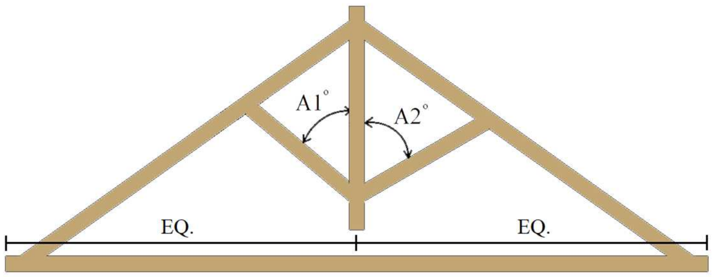

Figure 77 – Adjusting The Symmetry of the Frames of the Truss

A1.4. THIRD TRIAL

A1.4.1. Modelling Process of the Third Trial

Continuing on the previous approach of family creation, a new idea was risen to solve the previous issues, the approach is to divide the family into two sub-families, one is for the lower deformation "COSt-Capriata-MetaAlto.rfa" and the other is for the upper deformation "COSt-Capriata-MetaBasso.rfa", they can be added aside to each other to form a left part and a right part. The two families are sharing the name of the same parameters, as they are mirrored in the shape. However, each one has a parameter that identifies the height of the edge, as the frame in real life has a deflection in the middle sometimes it is a curved shape and sometimes it is a sharp inclination in the middle of the tie beam, this can be represented by an offset parameter at the edge of the family, in the upward direction in one family and downward in the other family, see Figure 79 and Figure 80 for more information.

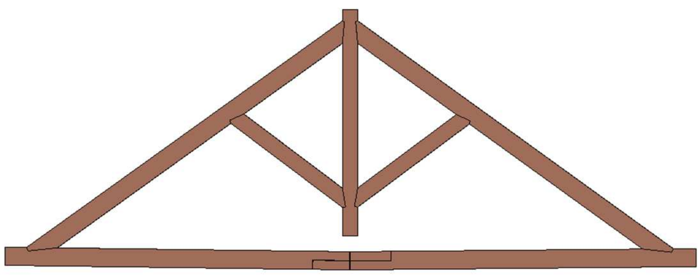

Figure 78 – The Two Families Assembled Next to Eachother to Form One Frame

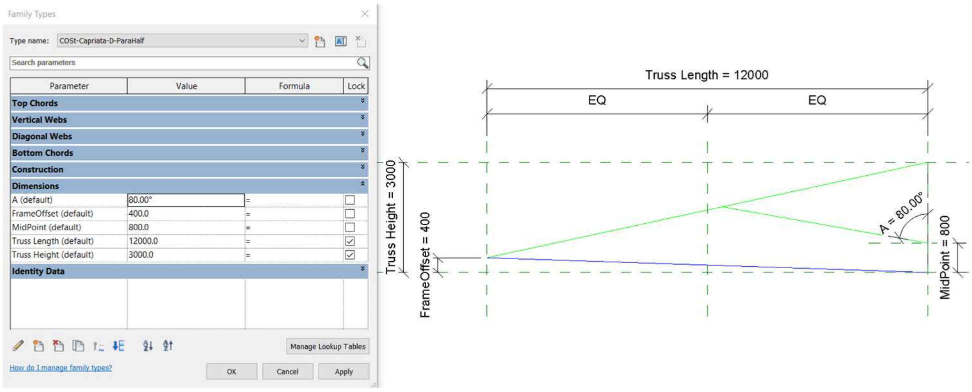

Figure 79 – Roof Truss Family With Upper Deformation (COSt-Capriata-MetaAlto)

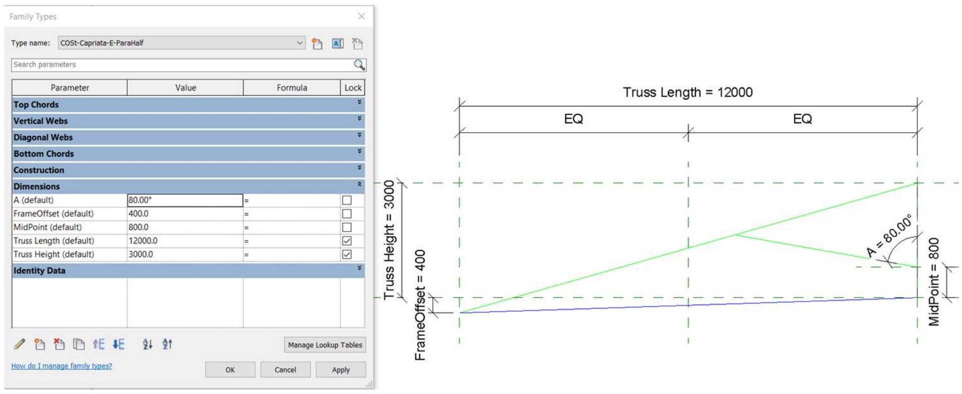

Figure 80 – Roof Truss Family With Lower Deformation (COSt-Capriata-MetaBasso)

A1.4.2. Results and Conclusion of the Third Trial

By allocating the frames in their right positions and the exact value of inclination that each frame held, the final model matched the point cloud in the arrangement, location, deformation, and the exact material added to give a realistic effect. You can see the difference between Figure 74 and Figure 81 to find the location of the tie beams and their positioning with respect to the point cloud file.

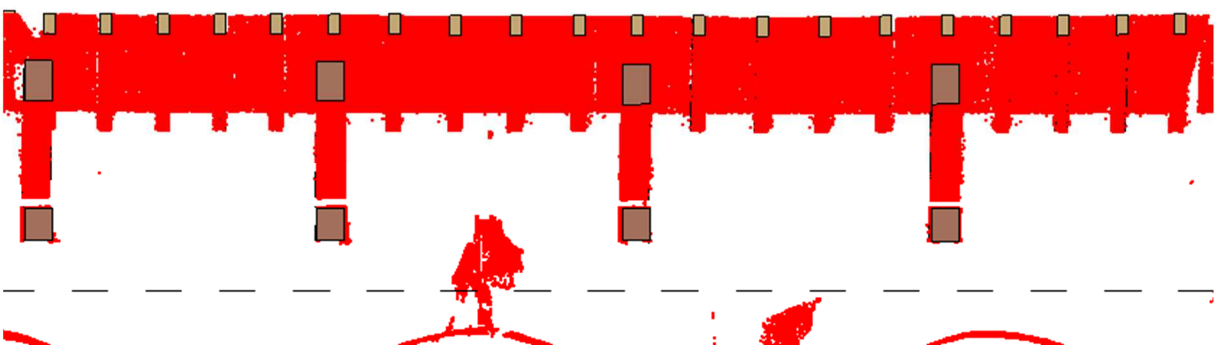

Figure 81 – The new Locating of the Wooden Frames Over the Point Cloud File

After modelling all of the frames of the roof, it was time to model all the purlins, common rafters, and ridge beams, the process was tracing the locations of their locations from the point cloud, see Figure 82 and Figure 83. The roof was deformed in the middle of the span from the bottom fibres, the tie beams of the frames, in addition to another deformation at the top fibres in the purlins and the common rafters, which led to the modelling strategy to divide these elements to create the deformation for each rafter separately.

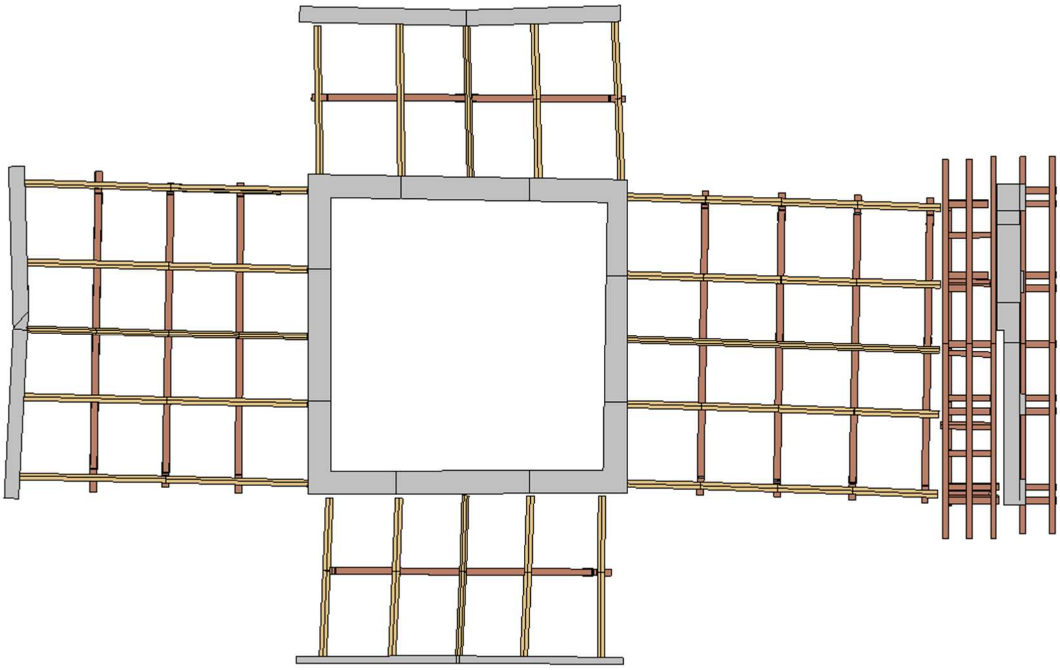

Figure 82 – Modelling all of the Frames, Purlins, and Ridge Beams Including the Old Frame on the Right

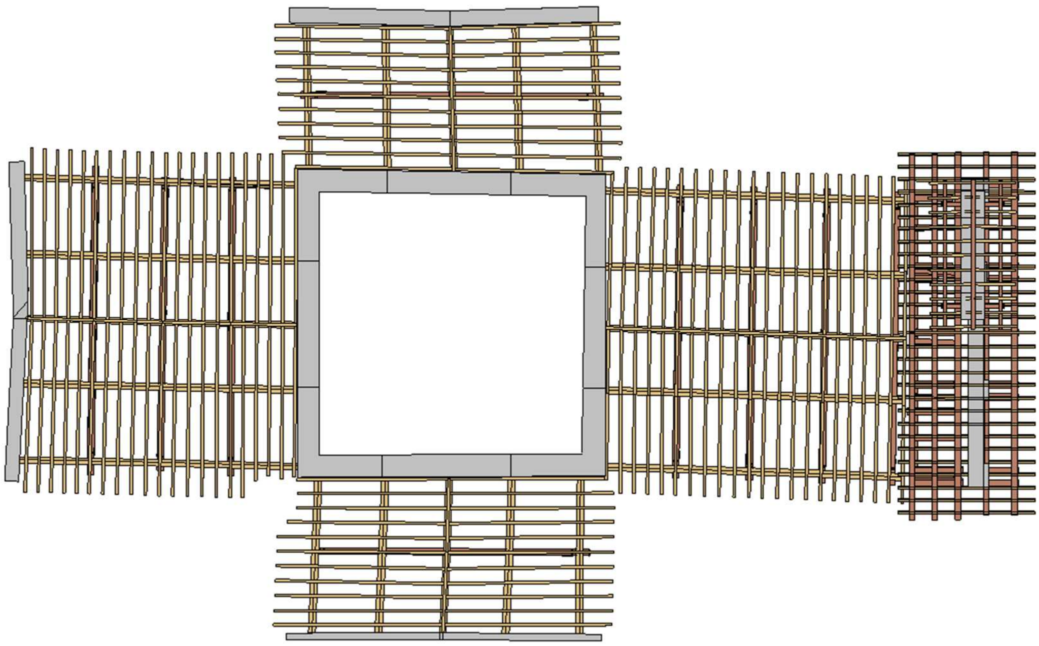

Figure 83 – Modelling all of the Common Rafters

A1.5. MODELLING THE OLD FRAME

The old frame was challenging and required a different strategy to handle it, as the software has a very good out-of-the-box library for structural trusses, this frame seemed not easy to handle using the families provided by the software. The family was straightforward and easy to use but for an ideal condition where all the sections are in good condition, and not deteriorated as we have in our case, see Figure 84.

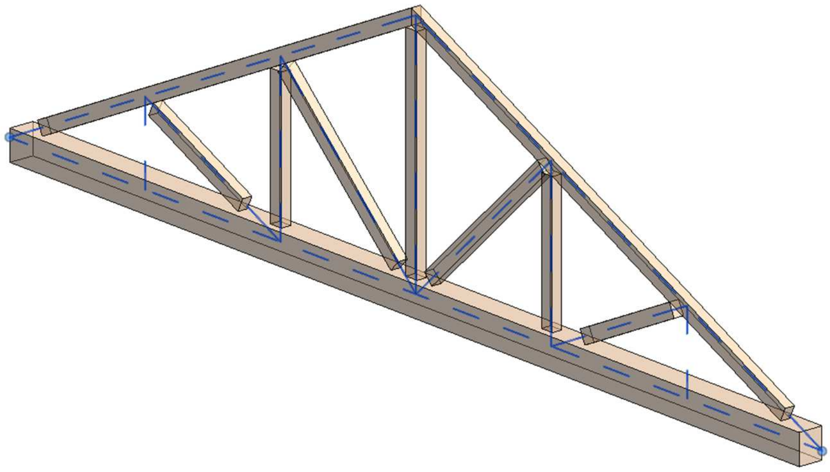

Figure 84 – Old Family Structural Truss Family

To resolve this problem, I used the family only to identify the positions of the members in the plan. Then, within the software, there is an option to remove the family outlines and maintain the geometries as structural frame elements. This option helped in the end to model the elements in the correct category and made it simple to move elements in the plan and adjust each element's start and end points in elevation as well.

Using this method, it was possible to keep around 80% of the frame's original form. The remaining steps in the modelling process involved determining the connections between these components as well as those to the new system and the façade wall. Because it was poorly maintained and had several metal strips to enclose the parts, see Figure 85.

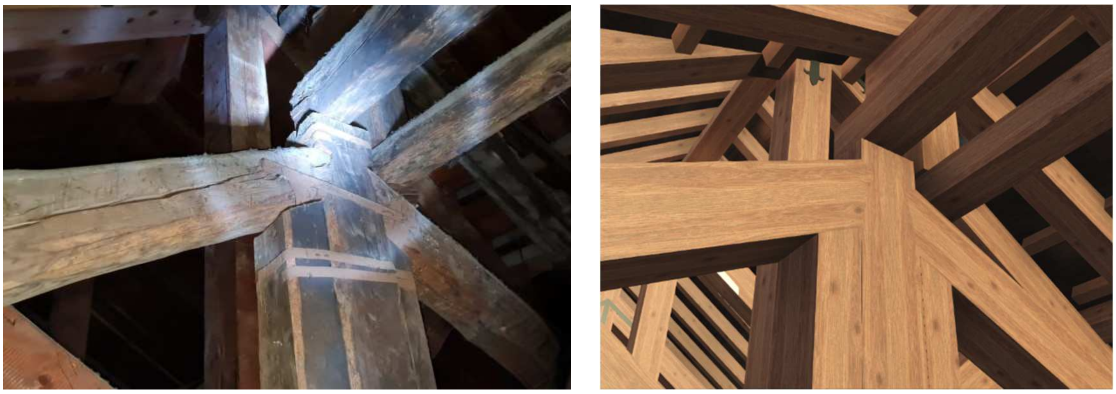

Figure 85 – Comparison at the Apex of the Old Frame (Real Life - HBIM)

A1.6. METAL BRACKETS FAMILIES

The metal brackets were created as generic model families, there were four main families for the new frame, while the old frame contained only one family. The first Three families were categorised as follows:

- The first one is “COSt-StaffaInFerro.rfa” which is modelled to connect the tie beam and the principle rafter, see Figure 46 and Figure 86.

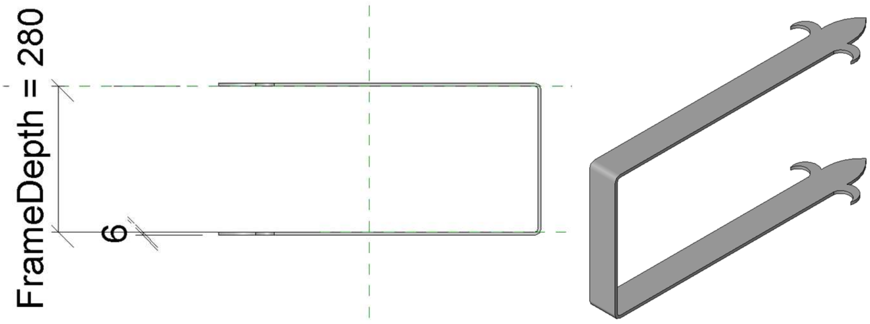

Figure 86 – Metal Bracket Between Tie Beam and Principle Rafter

- The second family is “COSt-StaffaInFerroSuperiore.rfa” which is modelled to connect the two principle rafters with the king post, see Figure 47 and Figure 87.

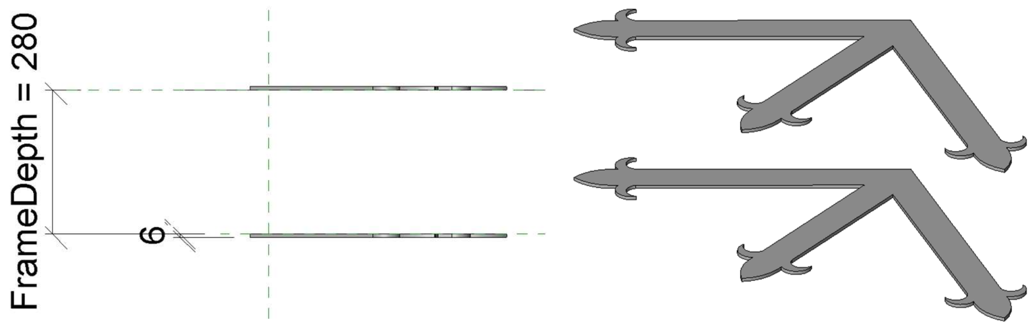

Figure 87 – Metal Bracket Between Principle Rafters and King Post

- The third family, "COSt-StaffaInFerroInferiore.rfa," is the lower bracket designed to confine the king post to the tie beam and prevent it from moving laterally, as shown in Figure 48 and Figure 88.

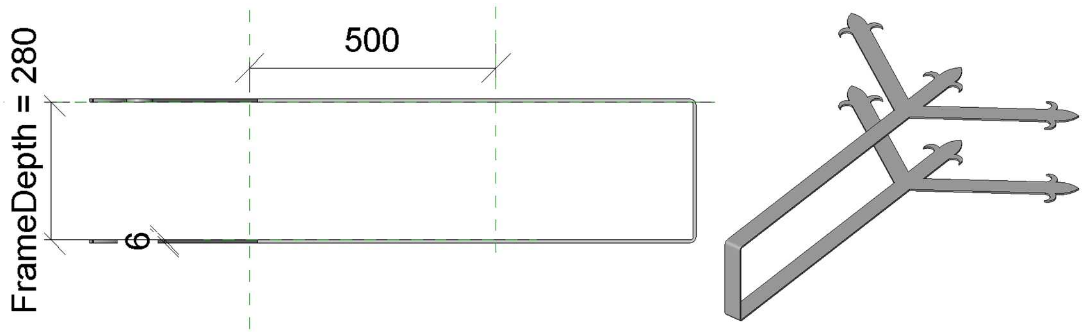

Figure 88 – Lower Metal Bracket for King Post Confinement

- The final bracket’s family, “COSt-PiastraDiAcciaio.rfa” is designed to connect the tie beam parts, it consists of two metal plates at the upper and lower of the beam, the two plates are attached to each other by four bolts with four nuts, See Figure 49 and Figure 89.

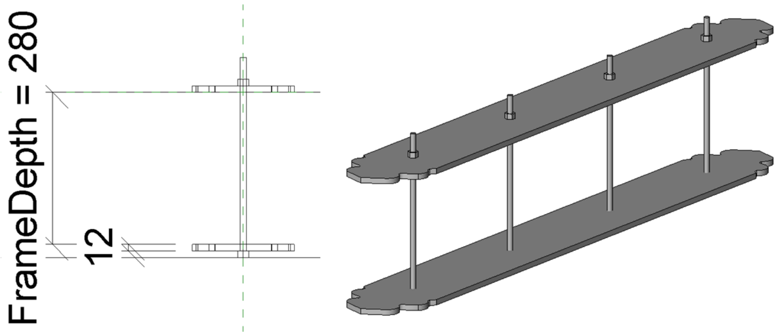

Figure 89 – Two Metal Plates at the Bottom of The Frame

The old frame is having a sole family that is similar to the third family in the new frame, however, it is less advanced, it was modelled as a single U-shape family with a parameter to control the depth of the frame, as shown in Figure 50 and Figure 90.

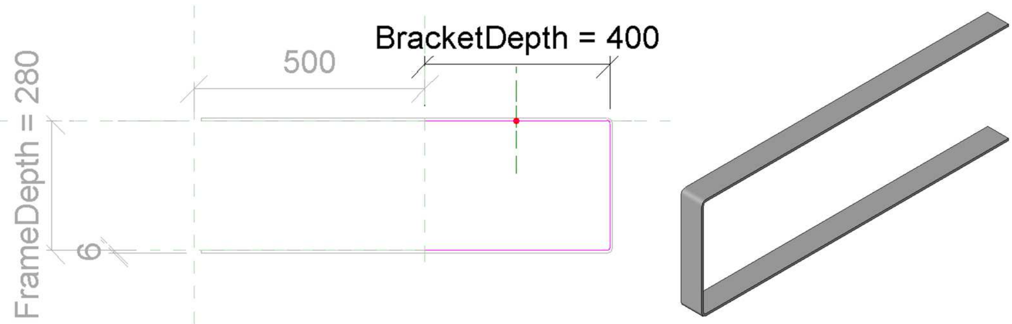

Figure 90 – Old Frame Metal Bracket

A1.7. MODELLING THE ROOF

The roof element needed to be created over these components as the last phase. In order to adapt each slab according to its slope and the actual deformation given to the roof, we first create a roof category element over the model and then edit the sub-elements of the top fibres at the corners, as shown in Figure 91 and Figure 92.

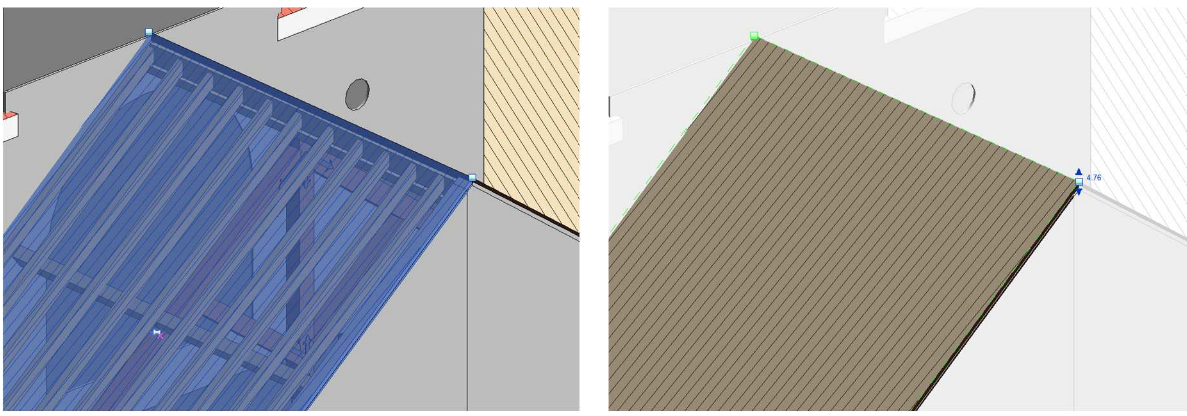

Figure 91 – Modifying Sub-Elements in the Roof Element

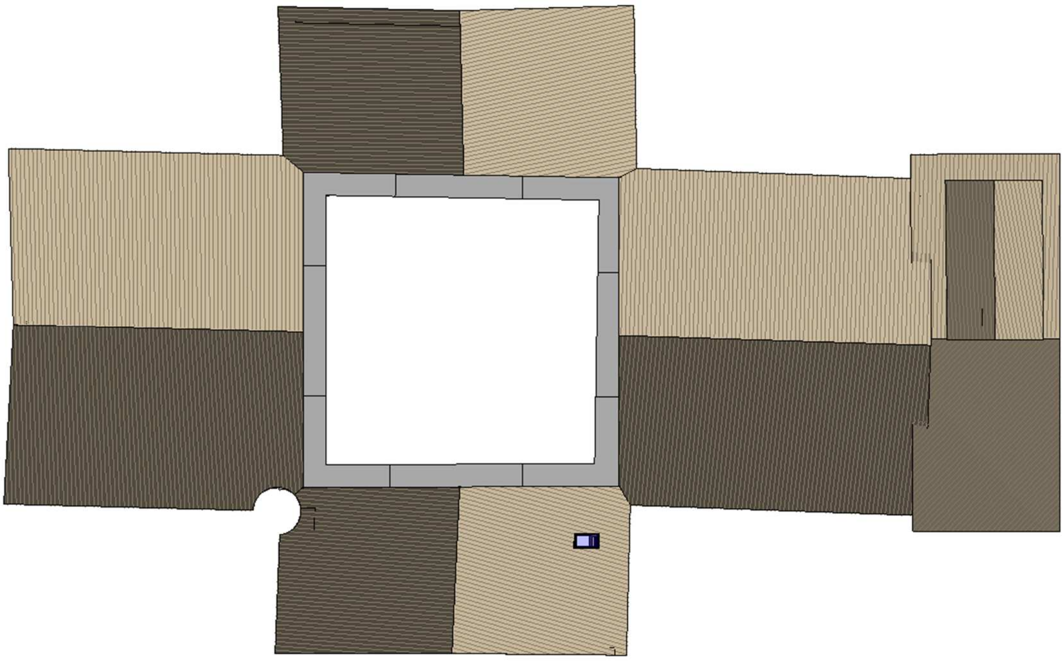

Figure 92 – Modelling the Roof Over the Structure

APPENDIX B: LOADS CALCULATION AND STRUCTURAL ANALYSIS

B1.1. PERMANENT LOAD CALCULATION

B1.1.1. Main Frame (Hardwood)

The weights of the major frames have been pulled from Revit using the scheduling tool, and an additional formula has been added to compute the weight based on the volume of the geometries. The following table summarises the total weight of each frame except for the old frame, as I considered that it was not carrying any roof loads, taking into consideration that it is located close to the façade wall, which carries the majority of the loads in the area surrounding it, including the own weight of that frame due to its fragile structure.

Table 3 – King Post Frames Own Weights

Frame Number	Weight (kg)
01	1,415.167
02	1,497.911
03	1,486.539
04	1,519.222
05	1,512.588
06	1,466.942
07	1,468.198
08	1,470.337
09	1,469.504

The table summarises the total weight of each frame except for the old frame, as I considered that it was not carrying any roof loads, taking into consideration that it is located close to the façade wall, which carries the majority of the loads in the area surrounding it, including the own weight of that frame.

We will select the first frame as it is the largest frame, and it carries more loads from the roof in terms of the loading span. The concentrated load of the frame is 1,415.167 kg, which is equivalent to 14.15kN. The total span of the frame is equal to 9.5 meters, while the inclined part of it has a length of 6.1 meters.

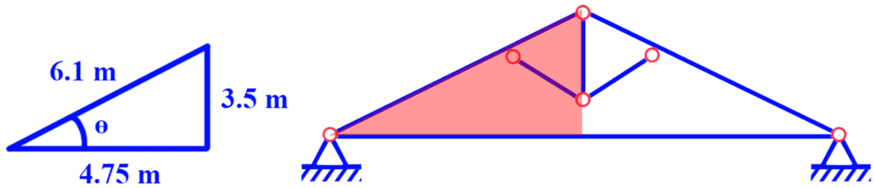

Figure 93 – Truss Geometry

The distributed load over one side of the truss is equal to:

$$w = \frac{14.152}{2} \Big/ 6.1 = 1.16\ kN/m$$

B1.1.2. Roof Loads (Softwood)

Similar to the same steps used in the hardwood load calculation, the total weight of the softwood was extracted from the Revit model as well. The total concentrated weight of the roof softwood equals 2,666.97kg, which is equivalent to 26.67 kN.

The distributed load over one side of the truss is equal to:

$$w = \frac{26.67}{2} \Big/ 6.1 = 2.18\ kN/m$$

B1.1.3. Roof Loads (Stone Slates)

Similarly, the total weight of the stone slates was extracted from the Revit model as well. The total concentrated weight of the roof tiles equals 3,402.07 kg, which is equivalent to 34.02 kN.

The distributed load over one side of the truss is equal to:

$$w = \frac{34.02}{2} \Big/ 6.1 = 2.79\ kN/m$$

B1.1.4. Total permanent Loads over the Roof

The total distributed permanent loads over the frame will equal to the hardwood's own weight, which is w_1=1.16kN/m, while the rest of the loads need to be concentrated over the purlins locations, as they act as supports for the roof, but first, we need to calculate the summation of the rest of the permanent loads acting on the roof as follows:

$$w_2 = 2.18 + 2.79 = 4.97\ kN/m$$

This load can be concentrated over the purlins by multiplying its value by the length of its influence along the frame length, as shown in Figure 66.

B1.2. SNOW LOAD CALCULATION

B1.2.1. Snow Load Standard Equation

The design codes used for snow loads calculations are (EN 1990 (03/2003)) for Basis of Structural Design, while the standard applicable for snow load calculation on this building is EN 1991-1-3:2003, and the snow load is identified by equation (5.1) in the same code (EN 1991-1-3, 2003), you can find equation (2) below:

$$s = \mu_i C_e C_t s_k \tag{2}$$

Where:

μ is the snow load shape coefficient

C_e is the exposure coefficient

C_t is the thermal coefficient

s_k is the characteristic snow load on the ground

B1.2.2. Snow Load Coefficient (μ_i)

Table 5.2 (EN 1991-1-3, 2003) shows the snow load form values that should be applied for pitched roofs. When snow is not stopped from falling down the roof, the values in that table apply.

For a pitch angle (α = 35º) we can obtain the value for (μ_i) which lies between 30º and 60º, the values can be calculated using the formula:

$$\mu_1(\alpha) = 0.8\,(60 - \alpha)\,/\,30 = 0.67 \qquad (3)$$

B1.2.3. Characteristic snow load on the ground (s_k)

The values of surfacic loads of snow on the ground $s_{k,0}$ (kN/m^2), corresponding to lower altitudes, are specified by the national annexe – Table C.1. (EN 1991-1-3, 2003). This one provides a country map divided into climatic zones.

$$s_k = (0.498Z - 0.209)\left[1 + \left(\frac{A}{452}\right)^2\right] \qquad (4)$$

Where:

A is the site altitude above Sea Level [m] = 208 m

Z is the zone number given on the map = 0.8

For the location of Como in the Mediterranean Region – Zone 2, the specified value of the load can be calculated by substitution in the equation above. Hence: s_k = 0.23 kN/m^2.

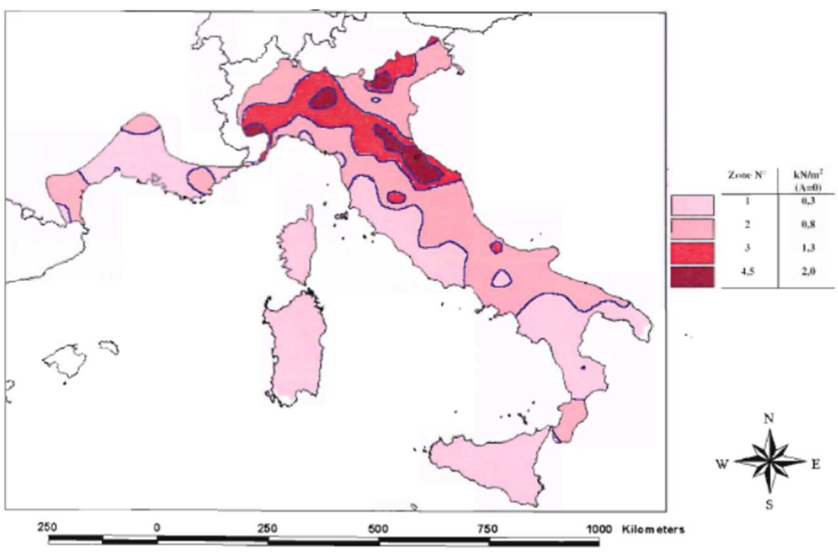

Figure 94 – Mediterranean Region – Snow Load at Sea Level

B1.2.4. Exposure Coefficient (C_e)

The exposure coefficient can be obtained from Table 5.1 (EN 1991-1-3, 2003), as the area where the church is built has a sheltered topography, so it is surrounded by other buildings. Hence the value shall be taken equal to 1.2.

B1.2.5. Thermal Coefficient (C_t)

The thermal coefficient can be taken as equal to 1, as we can assume that the reduction of snow loads on roofs with high thermal transmittance > 1 W/m^{2}K.

B1.2.6. Calculation of the Snow Load

By substitution in Equation (2), the value of (s_k) shall be as follows:

$$s = \mu_i C_e C_t s_k = 0.67 \times 1.2 \times 1.0 \times 0.23 = 0.185\ kN/m^2$$

B1.3. Using SAP2000 in The Analysis Process

By importing the geometry and calculating the loads, we can assign the loads to the members, define all the material's mechanical properties and cross sections, see Figure 95 and Figure 96, and run the analysis process inside SAP2000 with the Ultimate limit state combination taken into consideration.

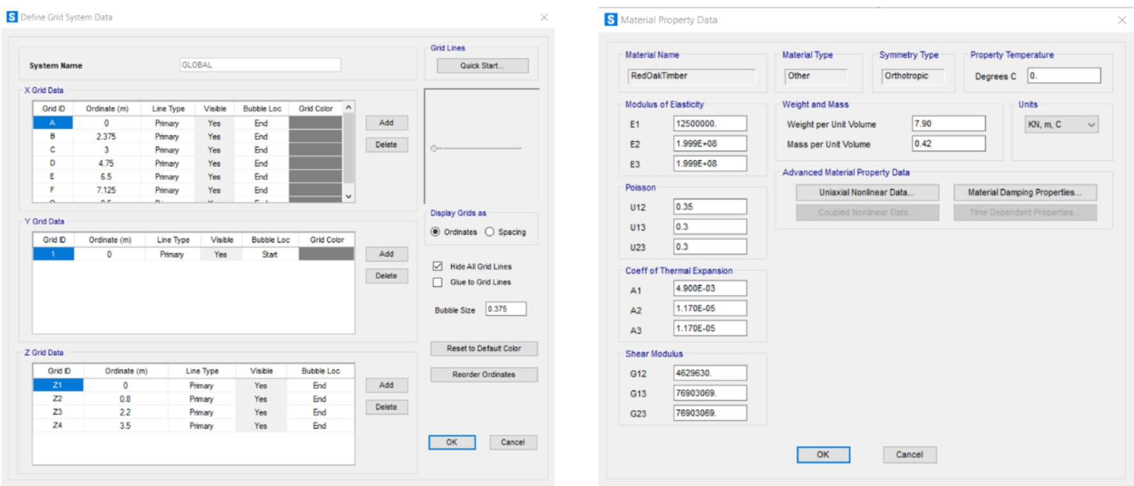

Figure 95 – Setting Up the SAP2000 File

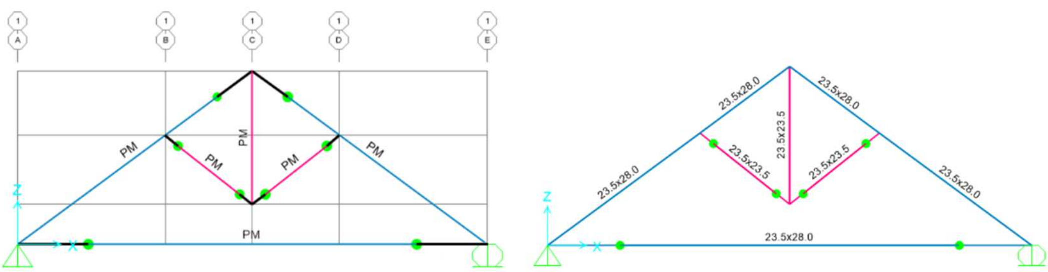

Figure 96 – Assigning Sections Properties and Boundary Conditions in SAP2000

The load combination used in this analysis is a combination between the permanent loads and the snow loads acting over the roof, the equation can be obtained from equation 6.10 in the Eurocode (EN 1990:2002+A1:2005, 2005) as shown below:

$$\sum_{j\geq 1}\gamma_{G,j}G_{k,j}+\gamma_P P+\gamma_{Q,1}Q_{k,1}+\sum_{j>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \tag{5}$$

Where:

ψ is the sensitivity factor: Category H for Roofs = 0.7
γ is the combination factor for permanent and imposed loads
G is the permanent loads
Q is the imposed loads

From Table A1.2(A) in Eurocode (EN 1990:2002+A1:2005, 2005), the value of "γ" can be obtained where γ_G equals 1.35 and the value of γ_Q equals 1.5 for snow loads, while ψ equals 0.5 for snow loads for buildings at an altitude less than or equals to 1000 meters above sea level. We won't include the impact of wind and seismic loads in this research, but it will be necessary to do so in future research because the building at issue is a historic structure and is quite vulnerable to loads. In addition, the zone where the building is located has a history of seismic acts in the past, as mentioned in a study about the effect of the 2004 earthquake on the historical churches in northern Itlay (Giuriani & Marini, 2008).

We shall calculate the straining actions acting on the building by making the appropriate substitutions in the equation above, keeping in mind that the only loads operating on the roof are the permanent load, represented by the frames, the weight of the roof itself, and the imposed loads, which are solely represented by the snow loads.

The load combination is made in SAP2000 to get the envelope results for all the axial loads and the bending moments acting over the frame's members, see Figure 97 that shows the loads' combinations setup in the software, in addition to Figure 98 where we obtained the frame reactions, and the straining actions acting on the members.

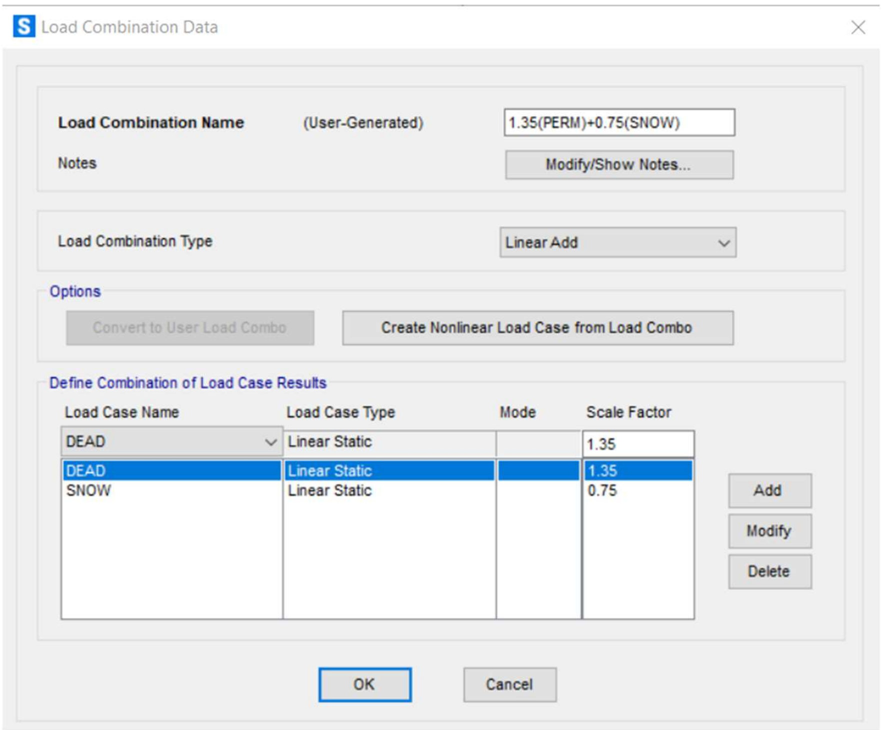

Figure 97 – Load Combinations in SAP2000

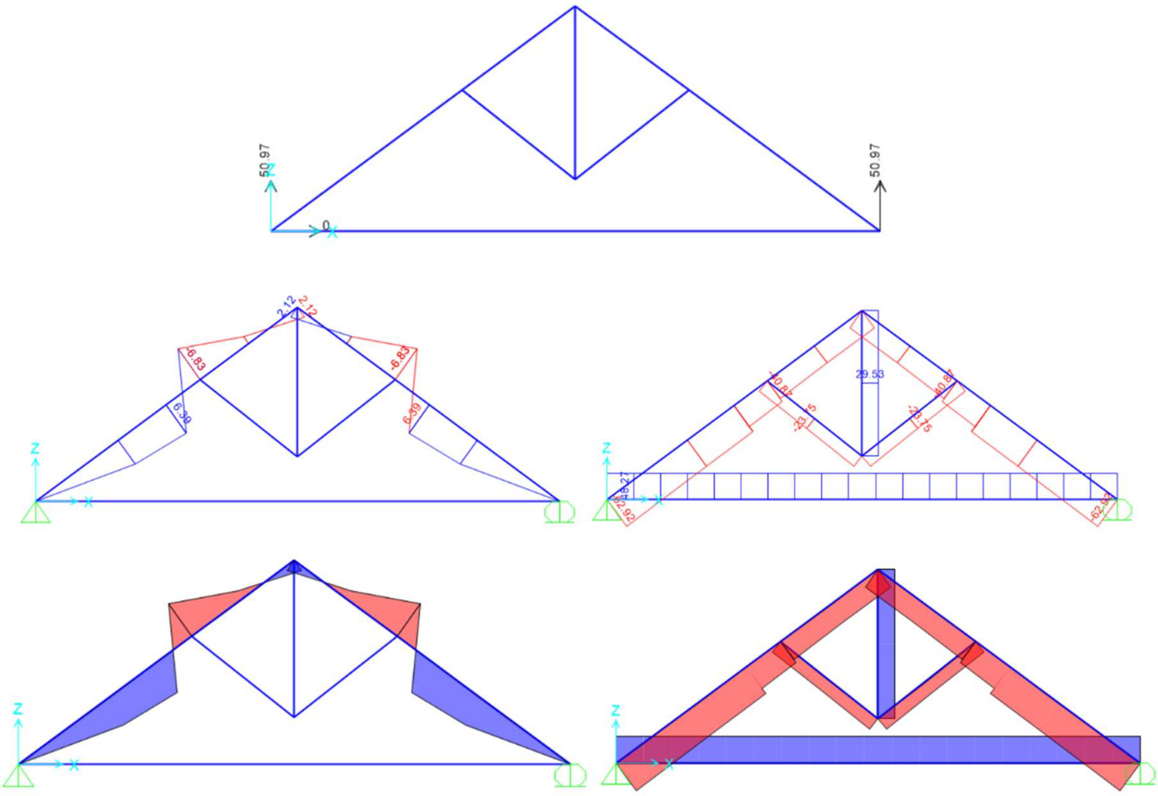

Figure 98 – Frame Reactions and Straining Actions of the Members

The final results obtained from the computer analysis of the frames can be summarized in the following Table 4:

Table 4 – Final Results of the Frames

	Value
Supports Reactions	**(kN)**
F_{xA}	0
F_{yA}	50.97
F_{yB}	50.97
Axial Loads	**(kN)**
Tie Beam	48.27 (Tensile)
Left P. Rafter	62.92 (Compressive)
Right P. Rafter	62.92 (Compressive)
Left Strut	23.75 (Compressive)
Right Strut	23.75 (Compressive)
King Post	29.53 (Tensile)
Bending Moments	**(kN.m)**
Tie Beam	0
Left P. Rafter	-6.83
Right P. Rafter	-6.83
Left Strut	0
Right Strut	0
King Post	0