ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

Sara Dimovska

BIM for Cultural Heritage information management.

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DECLARATION

Name: Sara Dimovska

Email: dimovska_sara@yahoo.com

Title of the Msc Dissertation: BIM for Cultural Heritage information management

Supervisor(s): Francisco M. Fernandes

Year: 2017

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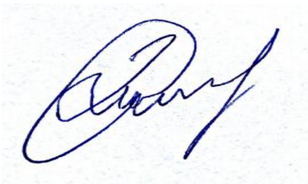

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I dedicate my dissertation work to my loving nephew Edi.

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ABSTRACT

Nowadays, Building Information Modelling (BIM) is one of the most used platforms for modelling new and modern constructions, made by regular elements and standard parameters. It is not just a software, but it is a process of creation and use of information about the construction, forming a solid basis including all decisions over the lifecycle of the structure – from the principal concept to the design, construction and management of the building. What can be used for the management, conservation and maintenance of the existing heritage buildings? Is there any possibility of using the BIM process for this purpose? The answer to this question is the goal and purpose of this thesis. It will be examined the applicability of the Architectural, Engineering, and Construction (AEC) industry's BIM with all its advantages and challenges to create a three-dimensional user interface for tracking and storing historic and management documentation.

BIM differs from traditional Computer Aided Design (CAD) systems because it includes both geometric and non-geometric data as object specifications and attributes. It is based on information enhanced parametric building elements, which are combined to create whole buildings within a virtual environment.

One of the most significant challenges of the Cultural Heritage is their preservation by acquisition of all information available usually from historical texts, architectural information, drawings, and photos, several visual inspections, geometry and photographic surveys. In order to have everything implemented in one file, without having to go over again with those tasks during the life time of the historical structure and to be able to share it between all team members of the project, BIM can be an adequate solution. Additionally, it has to be checked and confirmed if it can be used for the Cultural Heritage field, where has to be taken into consideration the complex constructive system made of different structural elements, their connections, the materials used, the degradation of the structures and their maintenance during its life time.

For this research, the church of São Vicente will be examined and modelled in order to assess the viability of the integration of all these aspects in the conservation and management of heritage buildings along time. It has been found that the modelling of the building takes time to build as the operator needs to assess materials and construction systems in a more careful way than traditional 2D drafting. However, it allows for a better documentation and storing all the information required to maintain and further study the building. It allows also the rapid assessment, planning and visualization of interventions. However, since BIM is currently more focused in new buildings, a series of challenges were also identified.

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RESUMO

BIM na Gestão da Informação do Património Cultural Arquitetónico

Hoje em dia, o Building Information Modeling (BIM) é uma das plataformas mais utilizadas para a modelação de construções novas e modernas, constituídas por elementos e parâmetros comuns. Não é apenas um software, mas um processo de criação e uso de informação sobre a construção, incluindo todas as decisões ao longo do ciclo de vida da estrutura - do conceito principal ao projeto, construção e gestão do edifício. O que pode ser usado para a gestão, conservação e manutenção dos edifícios antigos existentes e do nosso Património Cultural edificado? Existe alguma possibilidade de usar o BIM com esse objetivo? A resposta a esta questão é o objeto desta dissertação. Será verificada a aplicabilidade do BIM da indústria de Arquitetura, Engenharia e Construção (AEC) com todas as suas vantagens e desafios para criar uma interface tridimensional para a gestão e armazenamento de documentação histórica.

O BIM difere dos sistemas tradicionais de desenho assistido por computador (CAD) porque inclui dados geométricos e não geométricos, como especificações e atributos de objetos. Baseia-se em elementos de construção paramétricos melhorados pela informação, que são combinados para criar edifícios inteiros dentro de um ambiente virtual.

Um dos desafios mais significativos do património cultural edificado é a sua conservação através da aquisição de todas as informações disponíveis, geralmente de textos históricos, informações arquitetónicas, desenhos e fotos, inspeções visuais e fotográficas. Para ter tudo implementado num único ficheiro, sem ter que voltar a realizar algumas dessas tarefas durante o tempo de vida da estrutura histórica e para partilhar entre todos os membros da equipa do projeto, o BIM pode ser uma solução adequada. No entanto, deve ser verificado e confirmado se pode ser usado no estudo do Património Arquitetónico, onde deve ser tido em consideração o complexo sistema construtivo feito de diferentes elementos estruturais, as suas conexões, os materiais utilizados, a degradação das estruturas e sua manutenção durante o seu tempo de vida.

Para esse propósito, a igreja de São Vicente será examinada e modelada para avaliar a viabilidade da integração de todos esses aspetos na conservação e gestão do Património Arquitetónico ao longo do tempo. Verificou-se que a modelação do edifício leva um tempo significativo para finalizar, pois é preciso avaliar materiais e sistemas de construção de uma forma mais cuidadosa do que no caso de um levantamento 2D tradicional. No entanto, permite a obtenção de melhor documentação e armazena todas as informações necessárias para manter e estudar o edifício. Permite também a rápida avaliação, planeamento e visualização de intervenções. No entanto, uma vez que o BIM está atualmente mais focado em novos edifícios, uma série de desafios também foram identificados.

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РЕЗИМЕ

БИМ за информационо управување со Културното Наследство

Во денешно време, *Building Information Modelling (BIM)* е еден од најкористените платформи за моделирање на нови и модерни конструкции, направени од регуларни елементи и стандардни параметри. Тоа не е само софтвер, туку е процес за креирање и користење на информации кои се однесуваат на конструкцијата, формирајќи цврста основа, вклучувајќи ги и сите одлуки во текот на животниот циклус на конструкцијата - од главниот концепт до проектирање, изградба и управување со објектот. Што може да се користи за управување, зачувување и одржување на постоечките историски објекти? Дали постои можност за користење на БИМ процесот за оваа намена? Одговорот на ова прашање е цел и намера на оваа теза. Ќе се испитува применливоста на БИМ во индустријата за архитектура, инженерство и градежништво (AEC) со сите свои предности и предизвици за да се создаде тродимензионален кориснички интерфејс за следење и складирање на историска и управувачка документација.

БИМ се разликува од традиционалните компјутерски системи (CAD), бидејќи ги вклучува и геометриските и негеометриските податоци, како спецификации и атрибути на елементи. Овој процес се заснова врз база на информационо подобрени параметарски конструктивни елементи, кои се комбинирани за да се создадат цели конструкции во виртуелната средина.

Еден од најзначајните предизвици на Културното Наследство е нивното зачувување преку стекнување на сите информации што се достапни обично од историски текстови, архитектонски информации, цртежи, и фотографии, неколку визуелни инспекции, геометриски и фотографски истражувања. За да се вметне сé во една датотека, без да треба да се повторуваат активностите во текот на животниот циклус на историската конструкција и да може да се споделува помеѓу сите членови вклучени во проектот, БИМ може да биде соодветно решение. Дополнително, треба да се провери и потврди дали може да се користи за Културното Наследно подрачје, каде треба да се земе во предвид комплексниот конструктивен систем изработен од различни конструктивни елементи, нивните врски, употребените материјали, деградацијата на објектите и нивното одржување во текот на својот живот.

За ова истражување, црквата Св. Висенте ќе биде испитана и моделирана со цел да се процени одржливоста на интеграцијата на сите овие аспекти во зачувувањето и управувањето со историските конструкции со текот на времето. Утврдено е дека за моделирање на конструкцијата е потребно време, бидејќи операторот треба да ги процени материјалите и конструктивните системи повнимателно отколку со традиционалното 2Д цртање. Сепак, тоа овозможува подобра документација и зачувување на сите информации потребни за одржувањето и понатамошното изучување на конструкцијата. Исто така овозможува брза проценка, планирање и визуелизација на интервенциите. Сепак, со оглед на тоа што БИМ во моментов е повеќе фокусиран за новите објекти, неколку предизвици исто така беа идентификувани.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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1. INTRODUCTION

1.1 Motivations

Building Information Modelling (BIM) is a revolutionizing design, construction, maintenance and management process in new and modern buildings and infrastructures. One of the advantages of this model is to combine in a single and digital open format all the information regarding the structure throughout its lifecycle, namely: three-dimensional geometry, characteristics of materials, construction systems, manufacturers, etc. Additionally, BIM software enables the users to communicate and design, understand appearance, performance and cost in spatial and urban design processes. In this way, BIM has an enormous potential for providing 3D reconstruction, documentation and helping with the management and maintenance of cultural heritage buildings.

The need to preserve Cultural Heritage is becoming more important than the construction of new buildings. Despite its importance, historical buildings and monuments suffer from a serious lack of information: inexistence or not updated information regarding the geometry, construction systems and properties of materials, state of conservation, dates and information regarding past interventions done, manufacturers and entities involved, etc. In fact, one major problem is the availability of usable elements, such as drawings (most of the time in paper, out dated and scattered in a myriad of reports and studies), past interventions (materials used and where were applied, which techniques were used, constructors, etc.), access to existing information (private reports, information not freely available), etc. Additionally, interoperability is the key for the Building Information Modelling process, which allows systems to work together and exchanging design and construction data.

1.2 Objectives of the study

BIM is a recent advancement in Computer Aided Design (CAD) systems, which extends the capability of the traditional design methodology by applying and defining intelligent relationships between the elements in the designed parametric model. The idea is to have in a digital format all the information regarding the building (geometry, materials, constructive systems, manufactures, constructors, dates of interventions, location of the interventions, etc.) that can provide an easy platform for rapid update and management of the state of conservation of the building, plan of interventions, and, due to the already available geometrical information, it can be easily transferred to a proper software for structural analysis (in case of structural assessment) or for thermal and acoustic evaluation. Through a real case study is going to be explored the existing challenges related to the management of heritage structures. Therefore, the digitalization and the accurate representation of the historical structures create an initial knowledge database helpful for further maintenance and restoration works.

The objective of this work is to analyse the current Building Information Model to understand its advantages when used for historical structures and, more importantly, facing with the difficulties and challenges regarding surveying, conservation and management of Cultural Heritage.

In addition to 3D visualisation of the model, BIM can automate the production of digital documentation (3D, orthographic projections, elevations, sections, detailing, etc.) and design schedules, which can be very helpful for managing heritage structures. The parametric structural elements and objects can store data related to the object and its relationship to the whole building and are not defined singularly but as systems using interaction with other objects.

Having access to a BIM model of a historical monument can enhance visual inspections, project planning for interventions, improve information management, and increase the productivity, profitability and accuracy of a project done in the Cultural Heritage field. The main advantage of Building Information Models is the possibility to constantly collect and classify heterogeneous information as well as to manage the model through its life-cycle.

BIM should be used not only as a virtualising tool, but as intelligent software which provides design of 3D model and contains building component characteristics and other construction information. This thesis will be focused on assessing the modelling capabilities of historic buildings, data processing, use of available data to model structural elements, and providing a way to add mechanical information and use of the information for the maintenance during their service life period.

1.3 Thesis outline

The study is developed through literature review and modelling of an existing historical building. In the literature review, works of various scholars on the related topic have been presented with some of their results and conclusions for better understanding and further discussions. Additionally, the modelling has been carried out to check and confirm that BIM process can be used in the Cultural Heritage field.

The thesis is organised in eight chapters. The introduction as the first chapter explains briefly the motivations of the work carried out, main objectives and the overall organisation of the dissertation.

Chapter 2 presents the meaning, purpose as well as the advantages and disadvantages of BIM software. Also, a short historical review from the literature is given regarding the BIM platform in order to understand its development and evolution.

Chapter 3 introduces the novel approach for heritage structures called Historical Building Information Modelling (HBIM). In this chapter the current trends on the use of BIM in historical buildings are emphasized with mentioning of some examples of real case studies carried out.

Chapter 4 focuses on the challenges and difficulties in the management of heritage building, which will be discussed with some examples of case studies regarding this topic.

Chapter 5 presents the software ArchiCAD, a very well-known BIM platform, which is going to be used for the modelling of a historical building. All the possibilities that are given by this software will be presented together with the mention to the use of the Geometric Descriptive Language (GDL), in order to obtain a better accuracy of the 3D model.

Chapter 6 summarizes the inspection work carried out in the church of São Vicente by former SAHC master students, namely about the visual inspection, damage identification and non-destructive/minor destructive tests done. All the information obtained from this work was used to further increase the information of the parametric elements in order to provide and facilitate full life-cycle management of Cultural Heritage buildings.

Chapter 7 explains the creation of the parametric 3D model of the specific heritage building by implementing the basic structural and non-structural elements as well as the mechanical and other structural properties of the materials. The viability of the integration of all these aspects in the conservation and management of heritage buildings along time will be assessed. The results obtained will be presented with figures and tables.

Chapter 8 concludes the thesis with discussion of the results obtained from the work that was carried out. Also, it will be suggested some possible future studies that have to be done in order to improve the use of BIM for the management of heritage structures.

2. MEANING AND PURPOSE OF BIM

Building Information Modelling (BIM) is a process of creation and use of information about the construction, forming a solid basis including all decisions over the lifecycle of the structure – from the principal concept to the design, construction and management of the building. It is a platform to share all the knowledge in respect the building and to communicate between project participants.

According to the National Institute of Building Sciences - BIM has been defined as "*the act of creating an electronic model of a facility for the purpose of visualisation, engineering analysis, conflict analysis, code criteria checking, cost engineering, as-built product, budgeting and many other purposes.*"

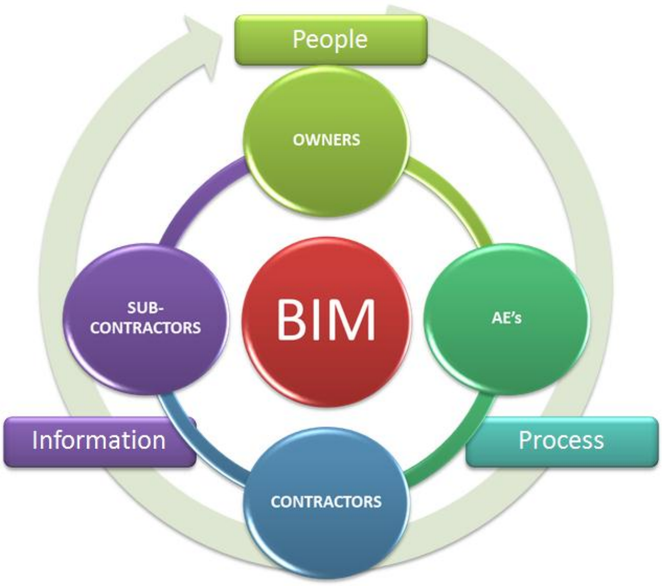


Figure 1 - BIM technology (WordPress, 2012).

The use of BIM technology is an effective tool for design and management in the Architecture, Engineering and Construction (AEC) industry (Figure 1). BIM as a widely used planning method can help interconnecting models with databases which supply different additional information. Any changes made to one of these databases are coordinated between each other, so that the consistency of the model is always assured. This is changing the way how designers collaborate with consultants and builders, and it guides the industry towards construction and management with sustainable development goals. It is still a novel technology mostly used for new constructions and therefore now is an appropriate time to investigate BIM and its applicability to existing and heritage structures. The advantages of BIM used for the design and life-cycle management of new buildings can be explored for their application in the documentation and management of heritage buildings and cultural landscapes (Fai et al., 2011). Furthermore, the challenges and the use of BIM in the management of the historical buildings will be addressed.

2.1 Definition of Building Information Modelling

Building Information Modelling - BIM is an integrative and visualisation tool for the design, representation, production, and long-term management of the built environment (Fai et al., 2011) and illustrated in **Error! Reference source not found.** The Building Information Model is primarily an intelligent, digital 3D model of the project, containing building component information and digital representation of a construction with its intrinsic characteristics throughout its lifecycle. It has a database that provides digital information about the construction, project management, design fabrication, building's material properties and logistics (Hergunsel, 2011). Therefore, BIM with its interoperability endorses information sharing between designers, engineers, owners and builders and coordinating all stages of the construction and management resulting in time and cost savings. It also provides consistent and coordinated views, and authentic representations of the digital model. BIM supports different processes such as project management, cost management, construction management, and facility operation management (Logothetis et al., 2015). This saves a lot of the designer's time since each view is coordinated through the built-in intelligence of the model.

According to the National Building Information Model Standard Project Committee (NBIMSPC) the official definition of BIM is:

"Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition" (Logothetis et al., 2011).

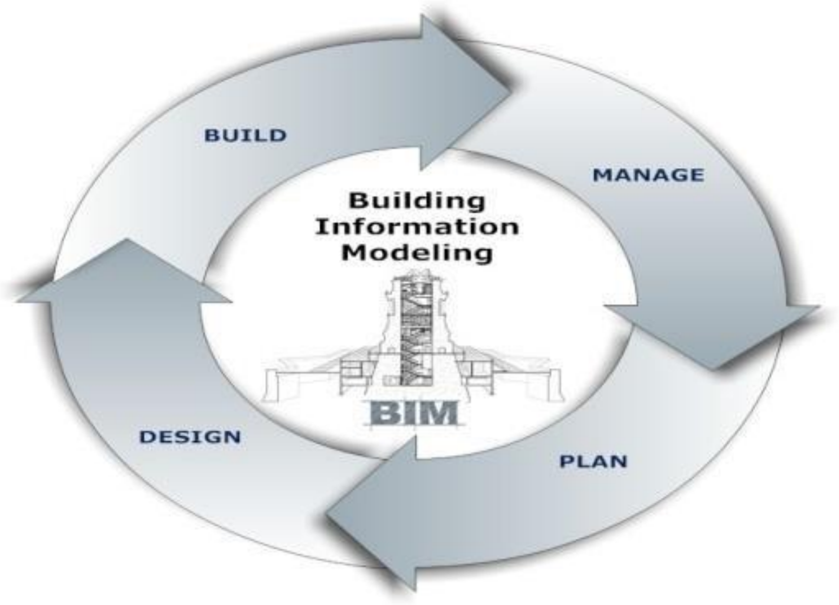


Figure 2 – BIM model (Logothetis et al., 2011).

BIM is a management process based on intelligent building components which include data attributes and parametric rules for each object. The Building Information Model including planning, designing, building and managing is utilized to communicate and manage through the project, securing valuable time and cost benefits. Using this technology the information can be presented in a more detailed way, containing data about the construction or restoration project such as: drawings, structural elements, constructive systems, mechanical properties of the materials, scheduling and financial data (Logothetis et al., 2011).

BIM means not only a digital representation of a 3D intelligent model, but also making significant changes and improvements in the workflow and project delivery. Additionally, Building Information Modelling aims to integrate people, systems and business structures all working on the same project into a collaborative process, by increasing efficiency in terms of time, cost and accuracy through all phases of the construction's life cycle (Azhar, 2011).

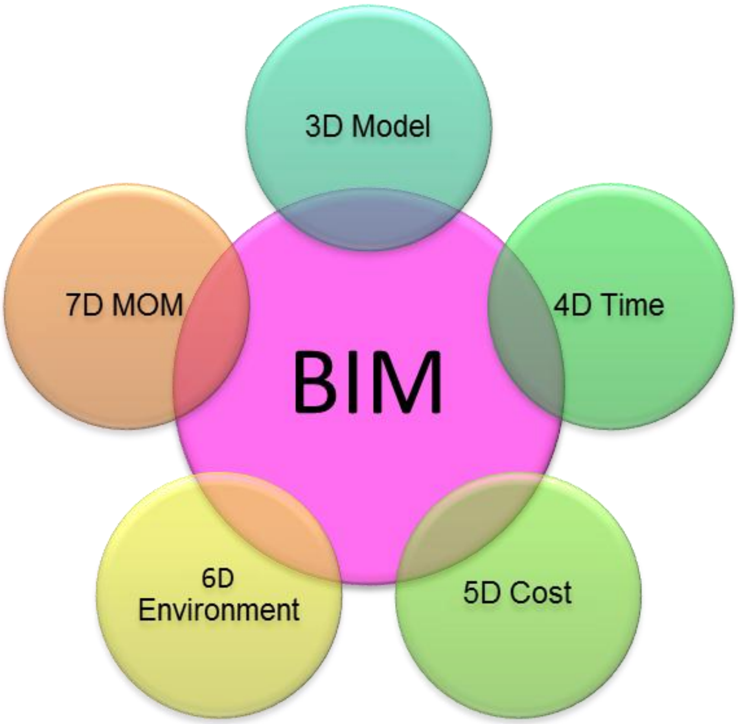


Figure 3 – The seven BIM dimensions.

Figure 3 illustrates that BIM has great potential in more than the three dimensions forming the digital 3D model of the construction. According to Barnes and Davies (2014), BIM has developed several dimensions. It revolves around an integrated data model from which different professionals can generate and extract views and information according to their role in the project. The 3D model provides authentic project visualisation, safety and logistics models, animations, rendering and walkthroughs, collision detection, virtual mock-up models, and prefabrication. This model enables participants to not only have a view of the structure in three dimensions, but also to automatically update these views along project's life-cycle. BIM 3D model gives more efficient multidisciplinary collaboration in modelling and structural problems. Furthermore, the fourth dimension is time, allowing participants to extract and visualize the progress of their activities through the lifetime of the project. The 4D BIM model is used for construction planning, scheduling, monitoring, and managing a project. The utilisation of this technology brings benefits to the participants in terms of planning optimization. By introducing some changes in the design, the advanced BIM model will automatically identify them and indicate what the impact will be on the overall delivery of the project. Additionally is presented the cost as the fifth dimension, with the ability to extract quantities, generate complete lists of orders, and use for budget tracking. A 5D model contributes for quantity take-offs, cost planning and 'real-time' cost estimation. Gathering all this information, BIM can give whole life-cycle cost estimation which benefits the development of more efficient, cost-effective and sustainable constructions. The sixth and seventh dimensions are referred as 'virtual' by some experts. The 6D model provides for improved space management, streamlined maintenance, detailed energy analysis, economical renovations, and life-cycle management. The utilization of 6D-BIM technology can result with complete and accurate energy estimates. Finally the seventh dimension is intended for facility management, operation and maintenance of the structure throughout its life cycle (Barnes and Davies, 2014). It allows project managers to extract some relevant data, specifications, maintenance manuals etc. The integration of the 7D model into BIM optimizes the management from design to demolition of the structure.

BIM creates a robust database of parametric elements in a single, well connected model which improves communication within the design and construction teams. The building owner, designer and facility manager can utilize the data incorporated within the model during the process of the project's' life cycle. Accumulating the information in that database can help everyone to create new opportunities and make them more efficient regarding the time invested in the project. Modelling, instead of drawing, and gathering all the information in one place with access to everyone on the project, is the new paradigm, fostering new cooperation, innovation and savings.

In other words, BIM is basically the creation and subsequent use of a computer-based model in order to plan, design, analyse, build, manage and maintain a building throughout its lifetime. The Building Information Model contains all elements of the building, their geometry, the way they are linked together, and also the texture and material properties. More precisely, BIM is a 3D-based framework designed to digitize and integrate all information needed for the structure so as to express all the building components and their relationships. Therefore, a constitutional characteristic of the BIM is its development through an information feedback loop. The evolution of the model and the accordant project information is cyclical (iterative); and as the project is being developed by the team members, the available information gradually increases in scope, depth, and relatedness. A coordinated and intelligent project will grow out of the building information that is continually cycled through the BIM at a more and more detailed and coordinated level (Mohandes and Marsono, 2015).

2.2 History of BIM (Literature review)

BIM is an extensively used planning and managing method in the construction industry of today. To trace back the history of BIM, it has to be explained firstly the beginning of the computer-aided design and computer-aided manufacturing (afterwards machining) technologies which were developed separately into the 60s. In 1957, Dr. Patrick J. Hanratty had developed the first commercial CAM (Computer Aided Machining) program. A short time after that, he dabbled into computer-generated graphics and in 1961 developed DAC (Design Automated by Computer) which became the first CAM/CAD system that used interactive graphics. Hanratty is regarded as the father of CAD/CAM since the two branches became into one.

In 1963, the first computer-aided design (CAD) with graphical user interface was Sketchpad developed by Ivan Sutherland. Overall, it was a program in which the user could graphically interact with the program and also was a major breakthrough in the development of computer graphics. In terms of construction technology, Sketchpad opened the way for solid modelling programs. His computational representation of geometry was further developed which allowed the ability to display and record shape information.

The history of BIM starts with the adoption of PC-based Computer-Aided Design (CAD) in the building industry in the early 1980s (Khodeir et al., 2016). The adoption of CAD software in Architecture firms was progressive and since then until nowadays it is commonly used by interconnecting different kind of data in the digital models required for the construction process. During the 1970s the transformation from 2D to 3D began and 3D CAD was introduced which at first was used as a presentation tool having not a very influencing role in the design process. The significant change happened when 3D CAD was used as a design tool and with it were modelled very complex shaped building.

The term Building Information Modelling or BIM was first used by Phil Bernstein from Autodesk. Another theory supports that Professor Charles Eastman extensively utilized the term in his books in late 1970 when he published a paper describing a prototype called Building Description System (BDS). In his paper, BIM was basically described as we know it nowadays. It discussed ideas of parametric design, 3D representations and some individual library elements which can be retrieved and added to the model. Afterwards, the term was applied by German Jerry Laiserin to represent the manufacturing process and to facilitate the exchange of data in digital form. Gábor Bojár released Graphisoft's Radar CH in 1984 for the Apple Lisa OS. This was later relaunched in 1987 as ArchiCAD, making ArchiCAD the first BIM software available on a personal computer. Therefore, the first implementation of BIM was under the Virtual Building concept was by the company Graphisoft with the platform ArchiCAD (Logothetis et al., 2015). Besides this software program, in 1987, Tekla completed its combined graphics and relational database for their early version of BIM software. By 2000 came up the software program called Revit which revolutionized BIM by using a parametric change engine and by creating a platform that allowed time attribute to be added.

In 1995, the International Foundation Class (IFC) file format was developed to allow data to flow across platforms which basically made a file compatible with different BIM programs. In 1997, ArchiCAD released its first file exchange based Teamwork solution. This revolutionized team collaborations between different platforms by improving the work in between individuals working on the same project.

Ten years later, in the start of the 1990s, object-oriented Computer Aided Design (CAD) was presented. Here, 2D and 3D drawings were introduced with implementation of objects, but still differs a lot from the geometric model computed with BIM. This agreed with the wide selection of 3D models in the building industry. When advanced geometry models begun to replace manual drafts on planning phases, organizers likewise started to determine additional information about objects and elements surpassing their geometric properties. By introducing 3D or currently with more than three dimensions digital models, it was offered very strong advantages regarding the interconnection and automation between the additional information which are coordinated so that with any changes made to one of these databases, the consistency of the model is always assured.

However, object-oriented CAD is still only an extension of the graphics-based CAD, which was not initially designed to store further information about the structure. Hence, it is called building graphic modelling, as opposed to building information modelling, which was introduced in the early 2000s as a reaction to these shortcomings (Eastman et al., 2011).

With this type of modelling, geometric models are generated, which can reflect conditions between the measurements of various parts or other interconnected properties by calculating them from a list of parameters. This additional information is important for the structural engineering which gives an even stronger focus on the inter-object relation in order to capture the design purpose of the engineer. This immeasurably enhances the interface between the mind of the engineer and the digital model. Always the main idea was to achieve a relationship and interconnection between the structural elements. As it was mentioned before, this likewise facilitates doing changes in the model, without losing any of the previous data inserted and it is always available to everyone working on the project (Khodeir et al., 2016).

In comparison between the CAD and BIM, it can be observed that BIM has a tendency to be a totally different and more innovative computer system from the Computer Aided Design. The use and purpose of BIM have turned into a disguised framework to incorporated data with a very stable connection between all the different information needed about a proper construction. Opposite from this, CAD gets the data required through outside sources. It is noted that "*a BIM model contains the buildings actual constructions and assemblies rather than a two-dimensional representation of the building that is commonly found in CAD-based drawings*" (Krygiel and Nies, 2008).

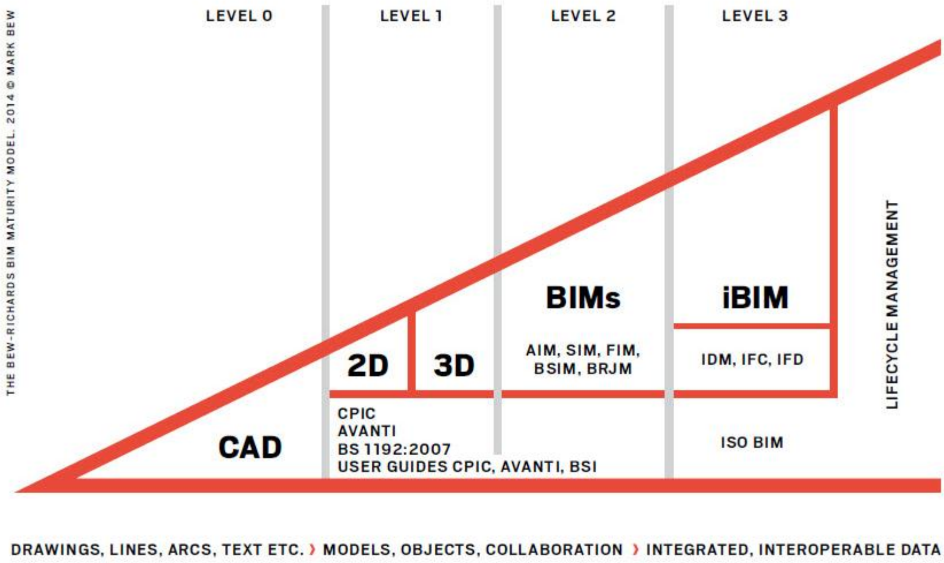


Figure 4 – Levels of BIM maturity (Graphisoft, 2015).

The Building Information Modelling software is being used at the moment at a number of different levels of sophistication. In the Figure 4, developed by Mark Bew and Mervyn Richards in 2008, different levels of maturity are graphically presented, where on the horizontal axis are presented the tools used corresponding vertically with the proper level (Graphisoft, 2015).

Level 0 is actually the undamaged computer aided design including 2D drawings which is essentially the start for any sort of BIM implementation. It defines the move from generating information by hand to creating 2D drawings and text with paper based or electronic exchange of information by using CAD software. Basically it is a digital drawing board which has zero collaboration and files are being shared either traditionally or digitally as separate information (NBS National BIM Report, 2014).

Level 1 is moving to managed CAD with the increasing introduction of spatial coordination providing a common data environment with a standardized approach to data structure and format. It includes 2D information and 3D information such as visualisations or concept development models. CAD standards are managed to BS 1192:2007, and electronic sharing of data is carried out from a common data environment (CDE), often managed by the contractor. This is the level at which most firms are operating. However, models are not shared between project team members (Epstein, 2012).

Moving from 2D and 3D drawings to 3D CAD models is the aspect of Level 2 of BIM. It is important how the information is exchanges between stakeholders, which mean not necessarily working on a single, shared model. These separate models are assembled to form a federated model, but do not lose their identity or integrity. It allows different parties to combine data or models and carry out a more validated audit on the project to reduce risk of errors and waste. Then it can be converted and shared with a common file format such as IFC. Commercial data will be managed by enterprise resource planning software and integrated by proprietary interfaces. This level of BIM may utilize 4D construction and 5D cost information.

Level 3 represents full collaboration between all disciplines by means of using a single, shared digital model. It is a fully integrated and collaborative process enabled by 'web services' and compliant with emerging Industry Foundation Class (IFC) standards. All parties can access and modify that same model, and the benefit is that it removes the final layer of risk for conflicting information. This is sometimes referred to as 'iBIM' (integrated BIM) and is intended to deliver better business outcomes. This level of BIM will utilise 4D construction sequencing, 5D cost information and 6D project lifecycle management information. Stakeholders of all discipline may access and modify the file by delayering risks of conflicting information (Barnes and Davies, 2014).

In the future, all members of the professional and construction team will have invested in compatible new technology, will have trained their staff, and will have fed design information, costing and programming information and other material into the single, centrally managed BIM model.

Many larger organisations are already making full use of available BIM systems, even they have some way to go to achieve the ultimate fully-integrated BIM level. It is likely to be some time before BIM systems are so universally used, and to such a high degree of sophistication. This new invented technology is the future for the AEC industry and it will be difficult to imagine working without it.

BIM is the future of the construction technology. Until now it seems to be accomplishing its massive potential to the architecture, engineering and construction sector. The integration of the virtual design, the human-computer interaction and the sustainable design of buildings has continuously and rapidly influenced the evolution of BIM.

Most recently Historic Building Information Modelling (HBIM) has been developed as a novel prototype library of parametric objects for heritage structures. The HBIM approach is new as most of the applications are applied for designing and managing new buildings. The potential in BIM that has been mostly used in the new construction fields can be adapted and refined for the management of the Cultural Heritage.

2.3 Purpose of BIM

BIM is the process used to generate and manage the physical and functional characteristic of places in a digital format. A BIM Use and Purpose can be defined as "*a method of applying Building Information Modelling during a facility's lifecycle to achieve one or more specific objectives.*" It is important to promote a better communication within the industry (Figure 5).

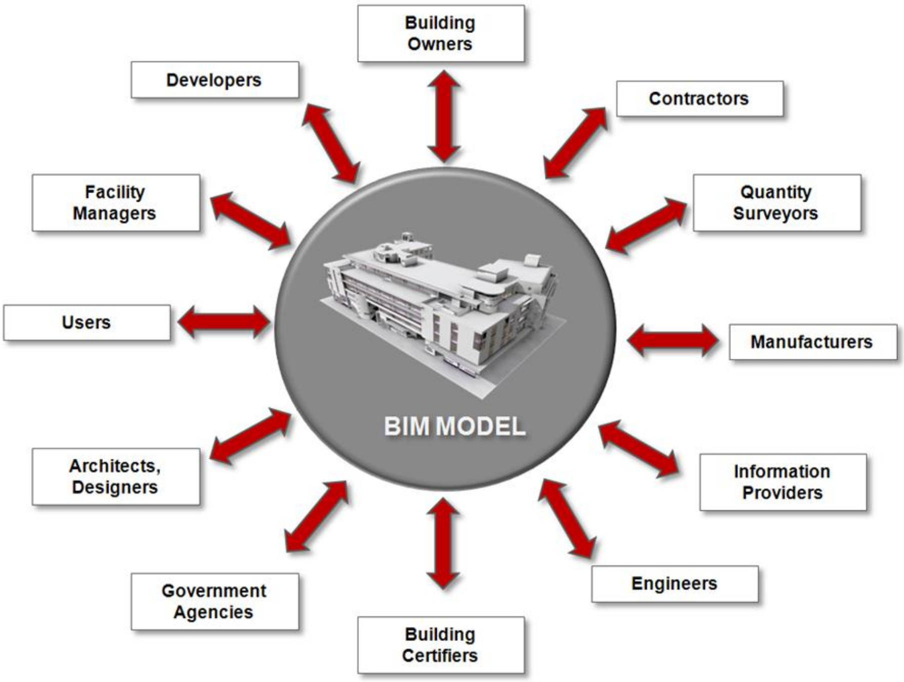


Figure 5 - Collaboration between team members of the same project (Graphisoft, 2015).

BIM provides advanced collaboration and information sharing between all individuals from different disciplines that participate in the project, by achieving its goals successfully. Considering complex construction processes, the purpose of BIM is to generate models and simulate the planning, design, construction and operation of a facility (Giel et al., 2013).

There are many basic capabilities of BIM, most of them aiming at: planning the strategy of building project design, construction and maintenance management; arrange integration management of graphical and informational data flows, associate the graphical interface with the information flows and process descriptions; implement individual tasks into complex processes; carry out life cycle operations of a construction project in a more effective, faster way and with lower cost (Logothetis et al., 2015).

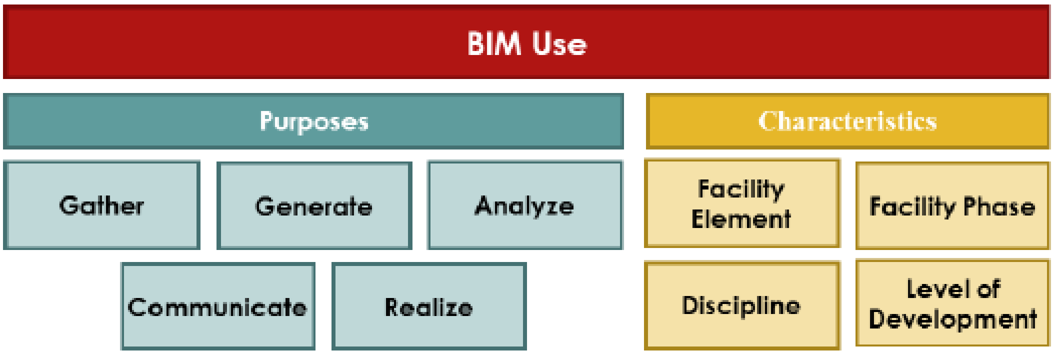


Figure 6 - The Components of a BIM Use (Kreider and Messner, 2013).

By implementing BIM throughout the life of a facility, its use can be classified by the purposes and characteristics which are defined at various levels (Figure 6). Its purposes are to collect or organize all the information regarding the structure; to generate or create information about the facility; to analyze, coordinate and validate the data of the construction and its elements in order to gain a better understanding of them; to present information about the facility by visualisation, drawings and documentation in a method where everything can be shared or exchanged and to make or control physical elements using the information provided (Kreider and Messner, 2013).

Nowadays, the use of BIM becomes more widespread in the AEC industry and it is used in all phases of design and construction, by helping visualize what is to be constructed in a virtual environment and determine the threats and weak points (Howard and Bjork, 2007).

BIM consists of information representing the entire structure with the complete set of design documents stored in an integrated database. By representing the entire life-cycle of the building, BIM aims at interacting with all the data and information collected which is parametric and thereby interconnected (Figure 7). It identifies different building elements (walls, slabs, windows, doors, and stairs) by their attributes (functions, structures, usage, and others) using parametric technology.

Any changes made to an element, object or its material will reflect immediately into the building configuration information by recognizing the relations between those attributes. Therefore, the characteristics of structural elements and their relational information can be obtained by simulation using the model data, which makes it possible to make rapid decisions during a construction project.

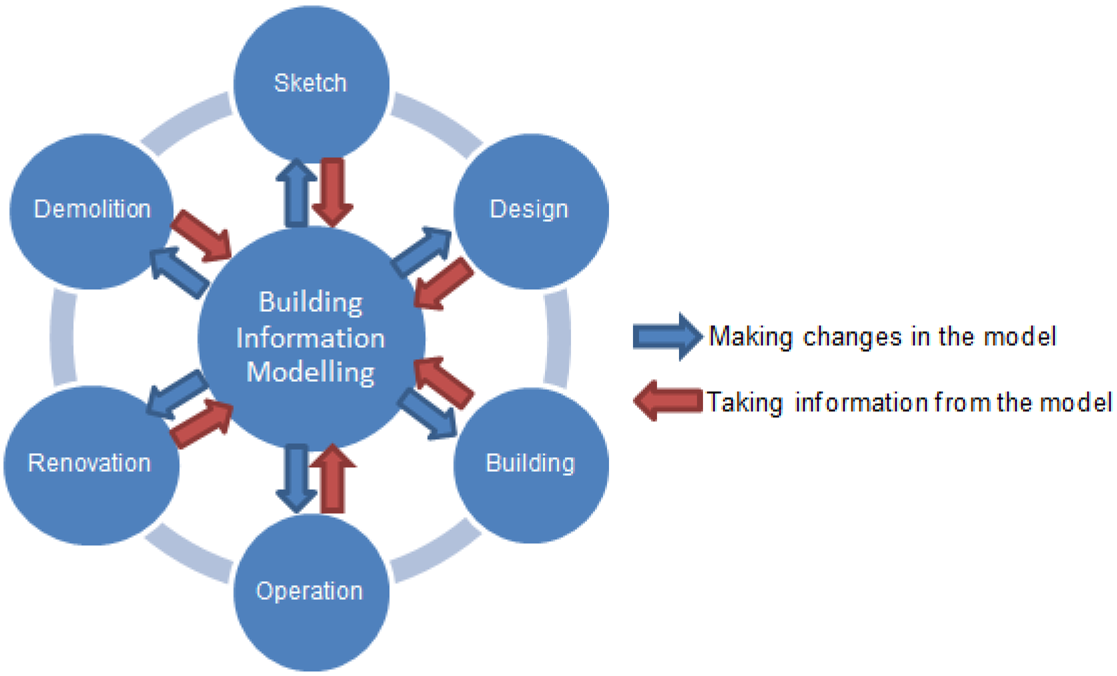


Figure 7 - Life-cycle of the building.

This technology is designed to support the work of everyone involved. Each member of the project starting from architects, engineers up to the owners and other professionals can have an overlook of the digital model, implement new ideas or make changes, which will result with faster and more efficient working, avoiding losing valuable time and cost benefits (Mohandes and Marsono, 2015).

In addition, the use of BIM does not stop after the construction, but begins the phase of operation and maintenance as a very important part of the life-cycle. Today BIM can be used for management of the renovation, restoration or demolition for existing and historical buildings (Cheng et al., 2015).

2.4 Advantages and disadvantages of using BIM

The primary motivation behind why the use of BIM increased so rapidly in the last couple of decades and most recently in the years is due to the tremendous amount of advantages it can provide for the planning, designing, constructing, managing and maintaining of a building. The definitive objectives of BIM are to expand productivity as far as time, costs, precision and thoroughness, to build correspondence, and to increase collaboration (Hardin, 2009).

One of the advantages is the implementation of minor, but significant changes in the digital model which permits fast modification without trading off all the work that has been already done by the team members of the project. Avoiding the conflicts and the mistakes that could be made during the process, it can save both time and money which is of interest for the individuals working on the specific construction project (Bryde et al., 2013).

Different professionals such as architects, engineers, interior designers and others can work on a 4D model and organize their work at the same time with the others just by applying changes which will be visible and implemented to every member involved in the same project. The execution of the work in this way enables individuals to coordinate and make more efficient their work, in the meantime by supervising the project in a better way (Hattab and Hamzeh, 2013).

Additionally, other points of interest that BIM provides for its clients are the way that computer models cannot decay with time, unlike paper documentation, and the likelihood to apply renovations to the model without creating or losing the previous one. In any case, maybe the most preferred advantage of BIM is the possibility for everybody required to work on the project on a model and in this manner enhance the team coordination and productivity drastically (Graphisoft, 2015).

This technology gives a correct illustration of the finished project which can be visualised at an early stage using this intelligent 3D digital Building Information Model. Models and their incorporated data are constantly updated, the communication of the design and engineering solutions is made less difficult and BIM allows for real-time design changes and development. In general, this usually improves communication and helps with the collectively work among project members (Hattab and Hamzeh, 2013).

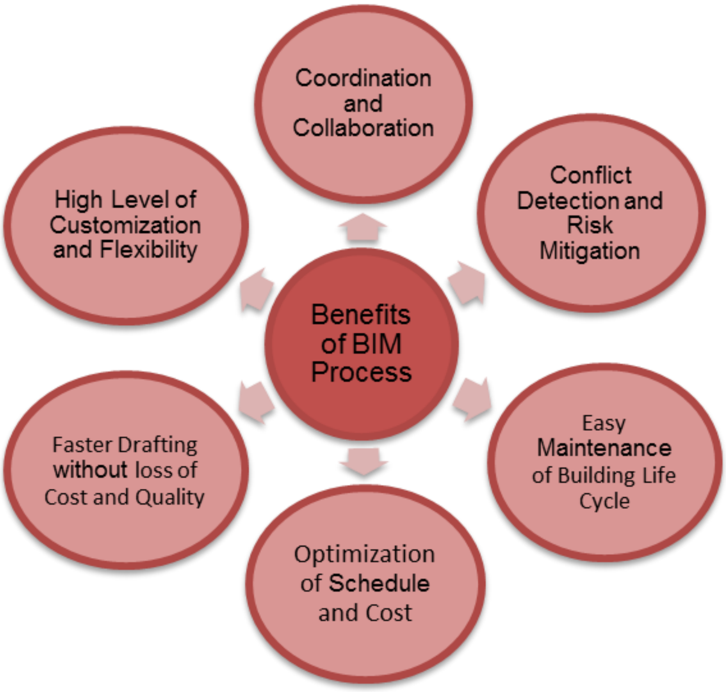


Figure 8 - Benefits of BIM Process.

Direct benefits of BIM are qualities, for example, the enhanced visualisation and the centralization of a construction data. The indirect advantages incorporate the need for coordination and collaboration, the subsequent better project understanding, optimization of cost and the reduction of the risk (Figure 8). Using simulations can help to arrange and essentially test a design before the project is fully panned. (Mohandes and Marsono, 2015)

Visualisation, collaboration, and elimination are the three fundamental characteristics, under which the benefits of BIM software are organised. These are among all the categories selected as the main ideas with which all the benefits can be better understood. Visualisation often addresses the benefit to an individual and the improvement in her or his personal knowledge as a result of using the BIM. Collaboration refers to the cooperative motion of different team contributors as this is recommended and facilitated by the use of BIM. Elimination addresses in the main project-related benefits, including diminution of conflicts, waste, and threat (Mohandes and Marsono, 2015).

Clearly BIM has a few disadvantages as every software platform, like the requirement for sufficiently powerful computers and the need for worker preparing on the software being utilized. Another real disservice is the value that the organization should pay for use of this product. Another issue is the reliability and the possibility to connect and work with other BIM platforms and utilizing the digital model for further structural analysis (Graphisoft, 2015).

All of the disadvantages should be taken seriously and sometimes the cost may be too high for the companies to afford to use this software. However the quantity of benefits that BIM provides to the people working in this business is immense, that slowly but firmly the expansion of BIM is growing and inevitable. Considering all before, this enlargement would most probable lead to the diminishing of some disadvantages just like the high rate of the software program and its “interoperability” with other software programs.

2.5 Importance of data interoperability and the IFC file

Interoperability can be defined as an ability to communicate between people or varying types of software systems. Effective communication is one of the most important factors in the construction environment. The collaboration between workers in the construction industry from designers to engineers can be improved by sharing the digital models for visualisation, organization, design and so on (Lee et al., 2011). In the AEC industry, interoperability allows systems and applications to work all together, by freely exchanging the design and construction data. This is a key for using the BIM processes across teams which are involved into projects. As our built environment becomes more digitalized and more dependent on the technology, BIM has become more used because of its interoperability.

Therefore, interoperability is the ability of distinct systems to share semantically compatible information and to handle and manage that information in semantically compatible ways, to empower their users to perform desired tasks.

One of the key issues of the building lifecycle management is that each one of the project professionals requires different types of information from the architect or the designer. BIM utilizes databases for storage and therefore having a possibility of close collaboration and managing a parallel access in order to keep the model consistent is a perfect solution for projects. This requires model management servers and is considered in the IT infrastructure with growing significance (Borrmann et al., 2009).

The objective of interoperability is to serve for sharing information and accomplishing some tasks, which cannot be performed completely by any subset of the frameworks being referred to. Additionally, there are many potential benefits that interoperability can offer:

- Flexibility increases;
- Creates virtually integrated systems that are easier to use;
- By allowing the reuse of existing systems and capabilities – cost-effectiveness increases;
- By composing new functions out of existing ones, it facilitates the creation of new capabilities.

Current improvement of IT construction is sufficient to make us perceive the significance of the development in the data model which has been based on the IT development in the AEC industry established in the past. Firstly, the construction industry has been converted from 2D CAD to 3D CAD for computerization of all information known for the construction and then into Building Information Modelling environment, by promoting integration and connection of all information and data regarding overall the life cycle of the structure (Ryu et al., 2016). Nowadays, BIM applications are capable to communicate with other programs by means of several file formats.

The Industry Foundation Classes (IFC) was developed in 1996 by the International Association for Interoperability (IAI) (Steel et al., 2012). It has an open format aiming for the interoperation of different BIM authoring tools by sharing construction and facility management data. As a standard universal framework IFC enables information sharing and interoperability throughout all phases of the building life cycle. The IFC file format supports interoperability and is an object-based, platform-neutral file format designed for transferring the 3D geometry and attribute information. It has seen a number of minor and major revisions, which help to improve the use for the BIM information (Lee et al., 2011). The IFC specifications are currently administrated by the BuildingSMART alliance as a global standard integration model to define the requirements for software interoperability in the AEC industry (BuildingSMART, 2017).

The professionals from this industry can use IFC to share data regardless of what software application they use to get their job done. Also data from one phase of the building lifecycle can be used in a further stage without having to re-enter some custom import interfaces (Figure 9).

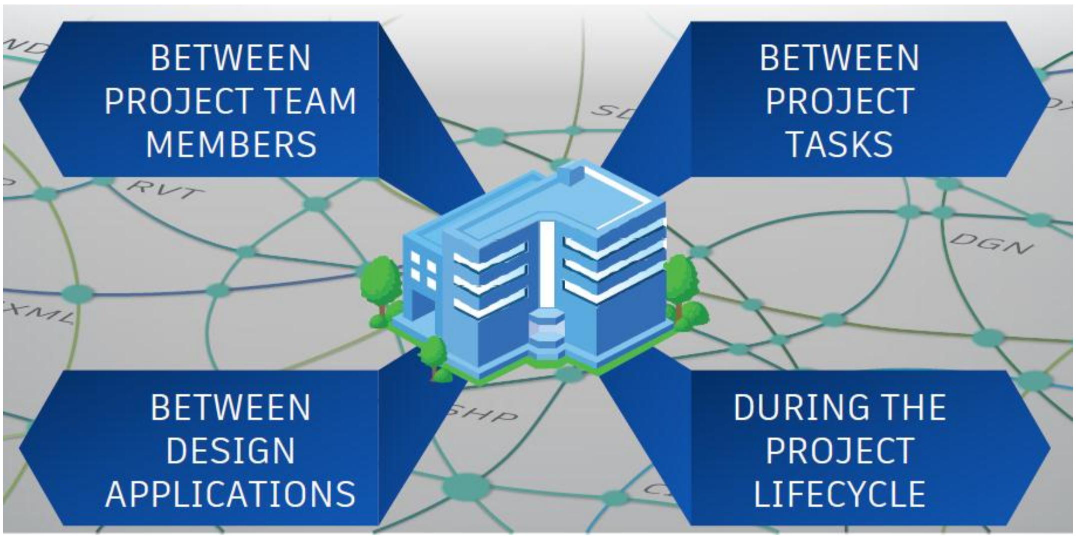


Figure 9 - Exchange of data with IFC file format (Di Giacomo, 2016).

Having standardized all the data and information available for the building throughout the lifecycle is a very important key to a higher efficiency in planning, constructing and managing the structures. To provide a comprehensive neutral data model able to present both semantic as well as geometric aspects is essential and crucial for enabling data exchange and open data access in the context of design, construction and maintenance.

The use of BIM tools has been expanded and to reap its benefits an exchange of information is required. The purpose of the IFC format is to enable exchange of intelligent building data between different software. In addition to geometry, IFC files contain important information about the type, properties and relationships of objects and composition of the building. IFC models contain a structures combination of geometric and non-geometric data. This data can be displayed, analysed and modified in different ways in multiple software applications. IFC is not only compatible for geometry information but also compatible for property information of the construction, and the standard protocol for data exchange in CAD tool representing BIM has been established for IFC (Ryu et al., 2016).

Some of the highlights of using the IFC file format are the following:

- Provides an universal, industry-standard data exchange format
- Exists a bi-directional connection between distinct applications
- Preserving the building elements with all the BIM information during the data transfer

Additionally, IFC provides a neutral data format file, enabling interoperability between systems and every data file produced by different BIM software can be compared and checked (Liebich et al., 2006). The IFC is an ambitious example of model-based interoperability, covering a wide range of modelling information. However it faces a lot of challenges that have to be overcome by improving its interoperability.

Transforming and exporting the native data into an IFC file is a way to exchange data from one software application to another. As mentioned previously the exchange format is open, free and well documented. By providing IFC export and import interfaces that conform to the IFC standards the owner of the application can to provide interoperability with hundreds of other BIM tools and domain applications (Figure 10).

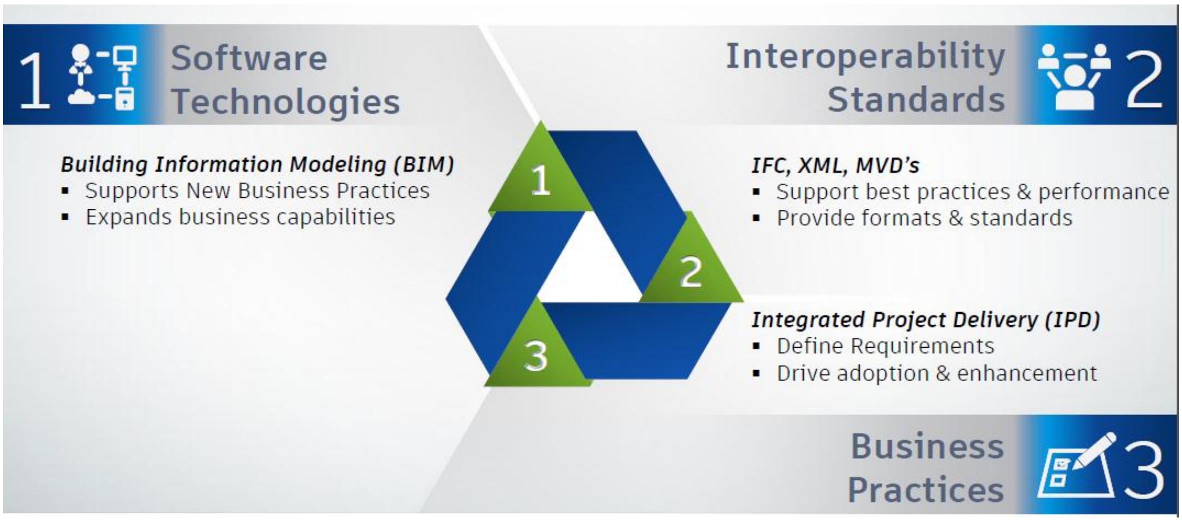


Figure 10 - Connection between BIM and interoperability (Di Giacomo, 2016).

With the increment of the project sizes, it becomes more and more important the extraction of partial models from the overall design for further collaboration, analysis and processing. Not all the individuals working on the same project require the complete digital model, but maybe a smaller subset of objects with which are going to facilitate their work extensively. This can be achieved by implementing the interoperability standards in the Building Information Modelling. Therefore, BIM objects with geometry, data and schedules can be exported from one originating application and then importing into another to continue design or analysis.

BIM applications are a governing force behind the IFC standard, by allowing free sharing and exchanging of the data from the 3D models between all different software related with building design, planning, construction and management (Figure 11). The main advantage of using the IFC file as a form of communication and collaboration between participants is that the BIM information is protected during the data transfer. Each element from the model stays the same by preserving all the previous 3D data after the IFC file is transferred and opened with another application. For example, walls will remain walls together with the attached properties to each element.

Engineers and architects, who are working on the project, use a variety of different specialized applications. Therefore, they can rely on the collaboration to interact with each other through the sharing of IFC files. IFC based model exchange ensures that the data will not be lost in the process and there will be done as accurate as possible the calculations from the model. This is a huge step for the effectiveness of the management change in the new and existing buildings.

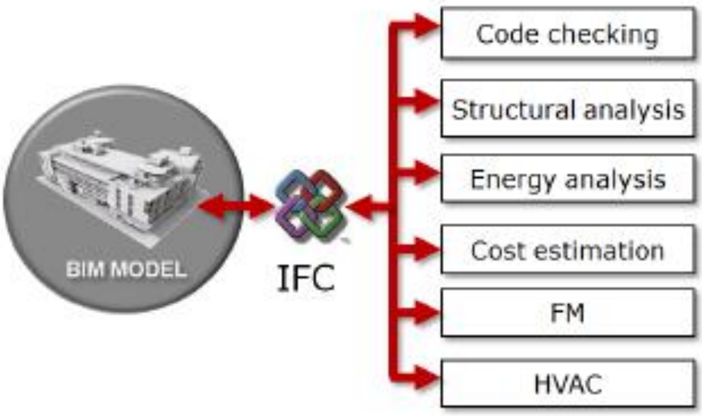


Figure 11 - Sharing the BIM data with other applications through IFC (Graphisoft, 2015).

The IFC platform provides a bi-directional connection between the BIM model and diverse applications such as code checking, structural analysis, cost estimation and HVAC design software (Graphisoft, 2015).

IFC and its use are very important for the design and construction industries and might be currently the best medium to exchange the building information between existing commercial applications. Therefore, the IFC file format appears to be sustainable based on industry software trends and it could be the most ideal approach to compare various data files in the near future.

3. HBIM: CURRENT TRENDS ON THE USE OF BIM IN HISTORICAL BUILDINGS

Historic Building Information Modelling (HBIM) is a special application of BIM for heritage structures, as a novel approach with a prototype library of parametric objects representing architectural elements based on historic data and accurately mapped onto a point cloud or image based survey (Murphy et al., 2013). These data will not just incorporate structural data, archaeological figures and historic texts, but additionally some administrative information and past drawings, sketches and photographs. Besides, it will also include current geometry data which can create as multi-dimensional perception with parametric databases in order to facilitate collaborative design and facility management (Cheng et al., 2015). The HBIM process includes the collection of the survey data using hand methods and lately a terrestrial laser scanner or photogrammetry (Cheng et al., 2015). In building parametric objects, the issue of file format and exchange of data has been overcome by utilizing Geometric Description Language (GDL) which allows the creation, sharing and altering of parametric objects at different levels (Dore et al., 2012).

Despite the fact that BIM mostly has been adopted for the design, construction and life-cycle management of new buildings, in the past decade there has been a growing development in the field of cultural heritage documentation which can change the way professionals can document and manage a historical monument .This method is a bit different from the actual BIM, because it tries to understand the historical structure with its construction phases, periods and changes (Logothetis et al., 2015).

Construction and documentation of existing heritage buildings in a 3D digital model is a complex task that typically involves a composite approach for visualisation of all the heterogeneous datasets such as survey data, CAD drawings, photographs, and 3D non-contact imaging data (from laser scanning, photogrammetry) (Fai et al., 2011).

BIM for existing buildings was first used in a research by Arayici in 2008. It promotes the usage of BIM software to move past the 3D visualisation through the joining of intelligent, multifunction and multi representational data (Logothetis et al., 2015). The study concentrates on adjusting the automatic data and information processing. Besides, in two other studies (Murphy et al., 2009 and 2011), they developed the Historic Building Information Modelling (HBIM) in order to integrate the new technology and BIM approach in the field of cultural historic documentation (Logothetis et al., 2015).

The trend to adopt the system BIM for the design, construction and management of new buildings is already accepted, but very little research has been made to explore its advantages in the documentation and management of heritage buildings and cultural landscapes (Cheng et al., 2015). Given this lack of appropriate documentation for many historic buildings, BIM generation could give a novel and important area of construction, management and technical research (Fai et al., 2011).

As mentioned previously, HBIM incorporates a plug-in library of architectural objects and structural elements for Building Information Modelling platforms and a system which is correlated with designing these objects (laser scan or photogrammetric survey data) (Cheng et al., 2015). In practice, the HBIM process actually begins with the collection and processing of information available for the historical structure, for example laser data and images, then identifying the structural details from historic and architectural books of which it can be created the database of parametric historic objects. Additionally it is done correlation of parametric objects onto laser data and finally the production of the survey drawings, plans and sections for the 3D historic virtual model. Also in the detailed 3D model can be included more details about the various objects such as construction materials, schedules for cost decay, energy and estimation of time (Logothetis et al., 2015).

As an example of a parametric library for historical objects which by the use of the historic data available gives the opportunity to develop their visualisation in details, the methods of construction and material properties can be seen in the Figure 12. These prototype libraries of different parametric objects are mapped onto the point cloud and image survey in the final stage of the HBIM process using a system of cross software platform management (Murphy et al., 2013).

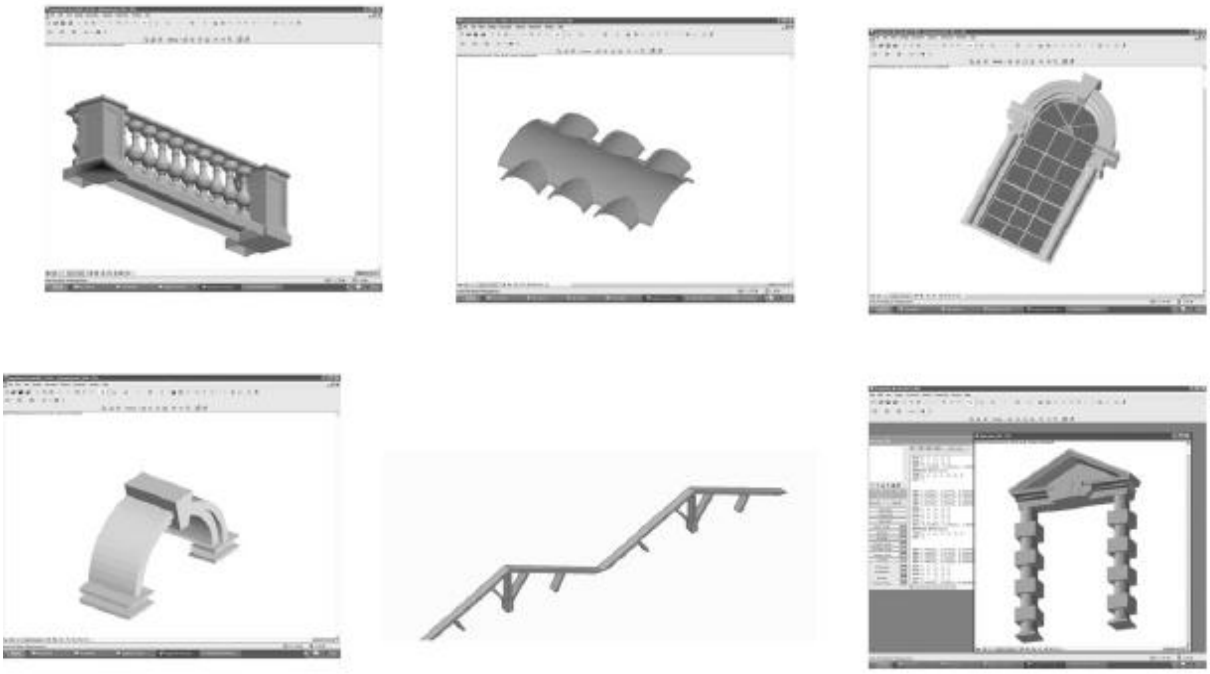


Figure 12 - Samples of object library (Murphy et al., 2013).

The final product is the creation of full 3D models including details behind the object's surface concerning its methods of construction and material properties. Furthermore, HBIM automatically produces full engineering drawings for the conservation of historic structure and environment which

include 3D documentation, orthographic projections, sections, details and schedules (Khodeir et al., 2016).
Modelling 3D heritage structures in a 3D BIM environment has its own benefits such as remote reviewing of the building from the exterior and interior, allowing studying it in an environmental context with new structures. Also there is a possibility to survey different period of time like different construction phases and better estimation of the building using images to understand the texture, massing and form. One of the important advantages for the cultural heritage is the restoration, renovation and adaptation using all construction documents with all the interventions and inspections done in the past. Most people can better understand a 3D digital model which gives an accurate visualisation of a structure than 2D drawings of different plants and sections (Logothetis et al., 2015).

HBIM tools can be used as a comprehensive data set of information about all disciplines, related particularly to the conservation of authentic and valuable buildings. (Khodeir et al., 2016) Using HBIM over other modelling approaches has a prior advantage that with the final result provides automated documentation in the form of engineering drawings for precise conservation of architectural heritage. (Murphy et al., 2013 In the heritage documentation, high visual fidelity, metric accuracy and the integration of multiple media types have been the prior consideration. Hence, this system provides highly sophisticated visualisation products developed from procedural and parametric modelling, taking into account the visualisation tool as the main product.

The main task of BIM is to generate a parametric model of a new or in this case an existing historical building including the details behind the object’s surface and will be involved also with the construction and documentation by using different approaches such as 3D laser scanning, recording, survey techniques and CAD drawings. The parametric databases are combined all together in order to facilitate the collaborative design and management of the heritage structure (Khodeir et al., 2016).

The interest in documentation and management of historical buildings has grown with the introduction of laser scanning. Also has been considered for preservation and restoration purposes by creating a 3D user interface for historic resource where the restoration or additions can be incorporated into the model in order to show the schedules, time, visualisation and optimization, cost of the new work to the investors, designer and building owners. Historical building restoration and reconstruction are one of the most significant challenges for the tangible cultural heritage. For these historical interventions, the first steps are the survey and acquisition of all possible data for the structural elements which will contribute to fundamental modelling for building recording and documentation (Cheng et al., 2015).

The process behind the work of Historic Building Modelling can be easily explained by the following diagram (Figure 13) where are connected the steps from collecting all the data and information known about the historic structure to processing them for creating the 3D parametric model.

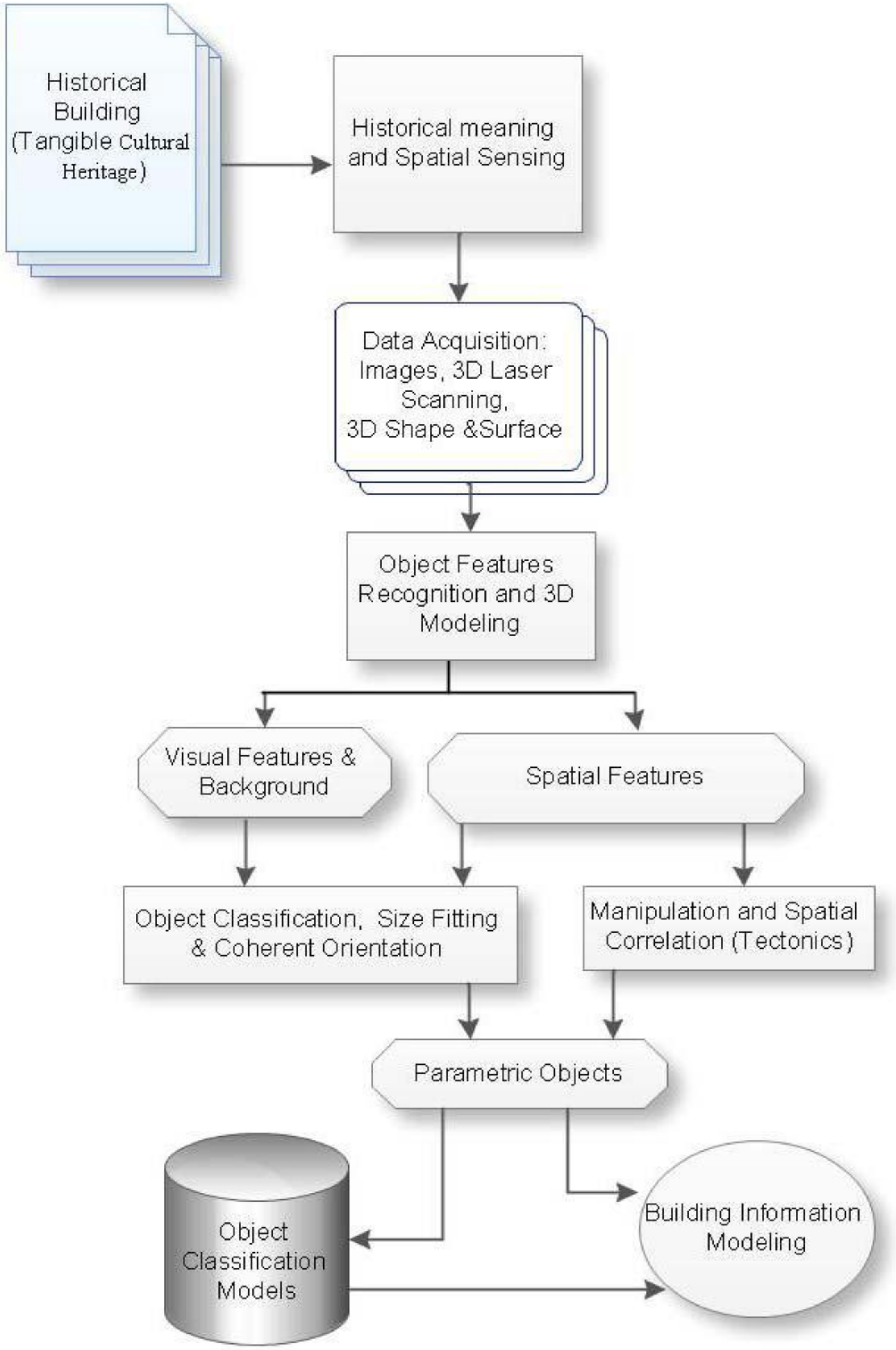


Figure 13 – Role of BIM in the documentation and refurbishing of architectural heritage (Cheng et al., 2015).

The focus on heritage documentation has taken a direction towards intelligent data as it pertains for the cultural analysis and maintenance of existing buildings. This new focus is due to the recognition of BIM as a novel technology addresses the growing demand for a multi-disciplinary knowledge base which is essential for the management of the building such as operation, renewal and development of the growing inventory of heritage sites. Secondly, there is a growing apprehending in the potential for BIM to contribute to the comparison of the compound relationships between tangible and intangible heritage (Fai et al., 2011).

The present approaches of historical building documentation and modelling are collecting, organising and integrating buildings' data into a single data structure by using the BIM tools (Eastman et al., 2010). The parametric building models are created by charactering building objects and the parametric connections among them. The digitizing and documentation at that point are consequently enrolled into a 3D space and surface with targeted points. The points on the 3D surface are independently becoming an observation overall the data, recognizing each object type, searching in a database of standardized objects, and adjusting calculations for optimal registration (Cheng et al., 2015).

In addition to the common advantages of Building Information Modelling in accomplishing prototyping, visualisation, collaboration, coordination, energy simulation, comparing different design options, solar study and energy demand prediction, HBIM is specially custom fitted to the application on heritage buildings (Khodeir et al., 2016). Hence, historical building modelling for digitization and documentation is the process of obtaining the spatial data and transforming it into a structured and parametric representation. These digital modelling and systems are generating useful information to designers, architects, constructors, owners, historical professionals and maintainers (Cheng et al., 2015).

With its multi-functionality at multiple scales, BIM can integrate the documentation of both tangible and intangible heritage into a single parametric object. Using IFC files and data, the digital model can be easily correlated to the materials and the methods of construction specific to the heritage documentation (Fai et al., 2011).

Historic Building Information Modelling, as plug-in for BIM, is characterized as a framework for modelling historic structures from laser scan and photogrammetric data. In general, the process of implementing HBIM includes a reverse engineering solution whereby parametric objects representing architectural elements are mapped into laser scan or photogrammetric survey data. With the use of laser scanning and photogrammetry can be recorded very high and accurate levels of detail in the field for historic documentation. It helps in establishing the details behind the object's surface concerning its methods of construction by using images to comprehend its texture, massing and form, and it can be considered as a dataset of information which can be used later on (Figure 14).

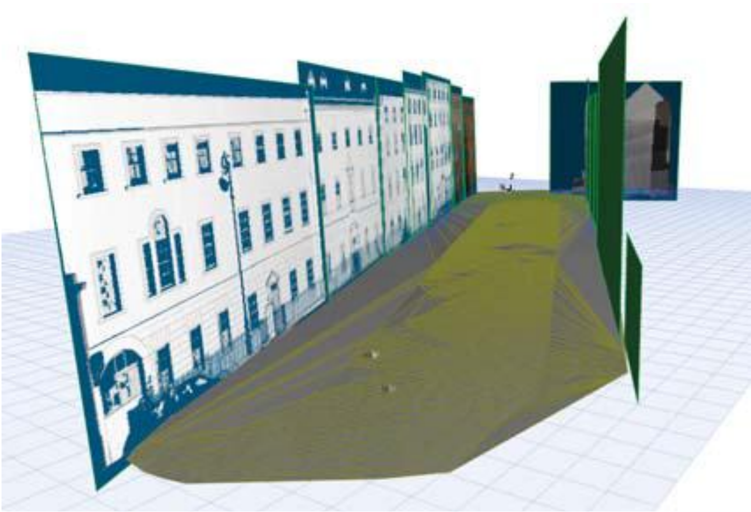


Figure 14 - Accurate integration of scan data into HBIM (Dore et Murphy. 2012).

The HBIM process can automate and accelerate the modelling stage by utilizing precise parametric objects that can be modified and mapped into the heritage survey data. Therefore, automated conservation documents such as plans, section and elevation can be produced as mentioned earlier (Dore & Murphy, 2012).

Moreover, the geometric accuracy of the models produced by HBIM will ensure reliable visualisation outputs that can enhance retrofitting. For creating a 3D surface through remote detecting (3D laser scanning) and then identification, extraction and modelling of objects are the two primary stages required to digitizing spatial modelling (Goedert et al., 2003.) In addition, HBIM provides review of the building's exterior and interior.

The procedure of HBIM which incorporates various stages to get the final product, starting with gathering and processing of laser/image survey data, recognizing historic details, building parametric components, objects and elements, and lastly correlation and mapping of parametric objects onto scan data with the final production of the design survey drawings (Murphy et al., 2013) (

Figure **15**).

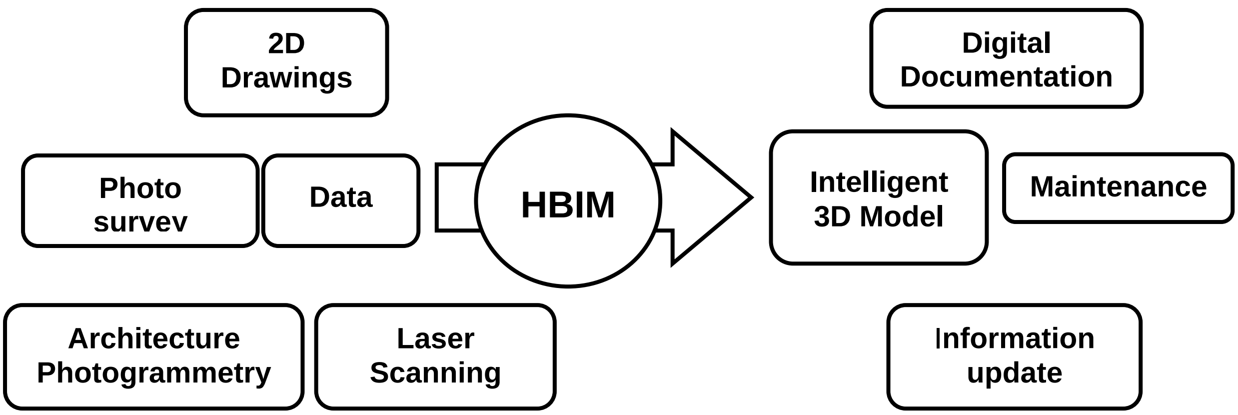


Figure 15 – HBIM approach (Khodeir et al., 2016).

Heritage buildings are crucial to the human perception of culture and identity through time. HBIM became a very well-known and important tool for the conservation and retrofitting of the cultural heritage. The reasons besides the endorsement of HBIM in the conservation and restoration of heritage buildings in general, and in sustainable retrofitting of such buildings in particular, are evident in the benefits of HBIM which exceed other modelling approaches, as it provides automated documentation in the form of engineering drawings for precise conservation of architectural heritage Additionally, HBIM facilitates the accessibility to survey renovations and changes that occurred through different time periods prior to committing to a strategy and produce full-construction documentation (Khodeir et al., 2016).

BIM in the field of heritage documentation and heritage conservation is a simulation tool for the integration of cultural, economic and performance criteria in the conservation and management of heritage structures. As heritage conservation is a significant process for prolonging the life of the historic building and the importance to preserve, take care and appreciate the past, BIM has proven to be a very good and useful tool for the help of management of the life cycle of the structures (Fai et al., 2011). For monuments maintenance and repair work, BIM system has to input the data to the element database and quickly simulate the process of reconstruction, repair or maintenance of the monument (Cheng et al., 2015).

4. CHALLENGES IN THE MANAGEMENT OF HISTORICAL BUILDINGS

Heritage structures are existing structures, or structural components of a resource, that have been recognised for its heritage value. These are broad and flexible concepts that refer to valuable buildings and constructions left by history and able to witness some development though civilization, meaningful development or certain historical events, urban or rural environment and certain historical events. Cultural heritage exists in time and space, and demands respect for all tangible and intangible monuments. The protection and enhancement of the cultural heritage should be accepted as an essential aspect of the human development (ICOMOS, 1994).

The fundamental principle of UNESCO is “the cultural heritage of each is the cultural heritage of all”. Nowadays, the conservation and management of the heritage buildings is an enormous responsibility as for the cultural community and for each human being.

According to the World Heritage Convention (UNESCO, 1972), the term cultural heritage refers to single monuments, such as architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, as well as archaeological sites and groups of buildings (Figure 16). Cultural heritage is universally recognised with a wealth of esthetical, archaeological, architectural, cultural, historic, documentary, social and even political and spiritual or symbolic values. This initial definition has been enlarged and nowadays in the characterization of cultural heritage it is possible to include also territorial systems, landscapes, itineraries and intangible heritage (Ferretti et al., 2014).

Figure 16 - Heritage structures.

According to the ''International Council on Monuments and Sites" (ICOMOS, 1987), *conservation means developing a place to preserve its ''cultural significance"*.

Conservation, by definition, means the retention of existing buildings, ensuring its material safeguard, without altering or destroying its heritage value, even though repairs or changes may be necessary (Curl, 2000). It should be taken into consideration the protection, maintenance and stabilization of the existing materials, forms and integrity. Conservation of historic buildings is sensitive to the preservation of as much original fabric as possible, and to distinguish new additions and changes from the original existing historic structure. Minimal intervention should be the guidance for the preservation of the monuments. Conservation allows considerable intervention on condition that changes done are of architectural and historic interest and enhance and respect the existing building character. It is a process that leads to extension of the life of the building and its utilisation. Heritage building conservation is a complicated task that follows some strict guidelines and procedures that always have to be respected (Azizia et al., 2016).

Building conservation is the way to protect built heritage in retaining its physical authenticity which represents a society's history and root. The common aim of maintenance of non-historical buildings is to retain the continuity of function, but for historic buildings, apart from continuity of function, protecting the building fabric itself equally is important due to its cultural significance – the building itself is an artefact. However in order to survive, heritage structures not only have to compete in inevitable changing of their authenticity by continuous frequent repairs, but are also threatened by the processes of natural decay as well as wear and tear of use (Mohd-Isa et al., 2011).

According to ICOMOS – '*'the overall objective of archaeological heritage management should be the preservation of monuments and sites in situ, including proper long-term conservation and curation of all related records and collections''* (Zeayter et al., 2017).

Heritage management is the most important part of an adequate conservation plan of old buildings. It involves investigation, documentation, interpretation, presentation and maintenance (ICOMOS, 1964).The first step in the global management of cultural heritage is the gathering of all the information about the historic monument, so it can be interpreted and understood (ISCARSAH, 2001). In general, the documentation involves investigation, historical research, survey of the geometry, construction techniques, materials, structural arrangement etc. All of this can be done by using some of nowadays new and most sophisticated technologies. For example, geometrical survey can be carried out using simple metric tape measurements, but also laser-scanner or photogrammetry. The inspection of the material properties can be done by sampling or by means of non-destructive and minor destructive techniques (NDT and MDT).

Cultural heritage documentation tasks usually involve professionals from different knowledge areas, which imply not only a huge amount of information and requirements, but also a very heterogeneous set of sources, data structures, content and formats. All this information has to be managed properly to be useful and to be used appropriately. Methods and process for life-cycle analysis and data management and maintenance of new and modern buildings can have a role in the management of existing historic buildings (Soler et al., 2017). For this, BIM, with its parametric model, was adopted as the main process to gather data for posterior analysis and management.

Furthermore, the data that has to be managed in the Cultural Heritage field together with the challenges and difficulties of using BIM platform will be explained. It is very important to verify the possibility of doing a representation of a parametric 3D model with all the information collected about its life cycle and all the inspections done during time. The visualisation of the historical structure is only a small part of the benefits from the 3D model that can be implemented in BIM. Implementing all the characteristics (architectonical, structural, constructive, materials and decays) into one single model instead of having many drawings, photo surveys, reports and papers, it is a substantial advantage of BIM. In addition, there are many challenges that have to be overcome regarding the difficulties that come from the digitalisation of the complex existing heritage buildings, their material properties, construction procedures, etc.

BIM offers to connect data and information to historic structures, with the possibility to perform queries and simulations on them. As it was mentioned previously, inside BIM has been developed an experimental process called HBIM which can help for the management of cultural heritage. It is a new prototype library of parametric objects and can be used for mapping parametric objects from a point cloud or image survey data.

In the research from Achille et al., (2015) are explained and elaborate the fundamental features that all BIM software should have to operate within the cultural heritage:

- To be able to gather historical-cultural and architectural information to understand where to operate;
- To anticipate the possibility of modifying or implementing, any time and by any professional, ensuring both the update of all the information linked to the different elements and the validity of the evaluations on the present state of the heritage;
- To assure the possibility of managing survey data (CAD, point clouds), to make easier the operation of virtual reconstruction of the building;
- To let the construction of an informative and open database, containing the indications about the materials and the constructive methodologies of the building;
- To establish the exchange of different information and collaboration between different parametric or nonparametric software, thanks to the use of open and non-proprietary file formats namely IFC, XLM, etc.

There are some operative issues that should be resolved, in order to fully use BIM systems for the conservation and management of cultural heritage:

- lack of interoperability between BIM and the technologies used for topographical survey; hard management of heavy and extensive data coming from surveying instrument (e.g. laser scanner, photogrammetry, etc.) like the extremely large point clouds, although this is being continuously addressed;

- complexity in the restitution of the unity and of the details of the historical elements;
- simplification of the geometry of the monument;
- inability to assign punctually specific data to points placed in the surface of the object.

The need to simplify the process for the creation of the 3D model and graphical elaborations for the cultural heritage became a goal not only for a correct reproduction of the existing monument, but also for a complete comprehension of the hierarchical logic between the parts of the monument (Achille et al., 2015).

4.1 Survey data

For the survey of a monument, an historical building or an archaeological area, there are three common methods such as the direct survey, the photogrammetric survey and the topographical survey, although with the use of the new technology available for those purposes, it is easier to obtain the data. For very complex or large buildings, the geometrical survey is mostly done with photogrammetry or laser scanning. This has been the focus of most of the research based on Historic buildings and BIM. Using these two methods, they generate one product – the point cloud – through different means. The management of point clouds is still one of the biggest problems of BIM applied to heritage structures, and is still an issue faced by several design platforms. Nowadays, the main software players are able to import point clouds, but it is crucial to accentuate that is not easy at all to manage them (Achille et al., 2015). The researchers from this study established that the most common problems with opening the point clouds in two of the most well-known BIM software for building design, namely Graphisoft ArchiCAD and Autodesk Revit, are the following:

- Impossibility to import big point clouds (with millions of points), making it impossible to reach a high level of details;
- Impossibility to recognize the points as snap points and redraw the profiles;
- Impossibility to edit the surfaces created with triangulation.

To solve part of the problems mentioned earlier, some plug-ins are available, for example, Green Spider for Revit developed by Garagnani and Manferdini and Cadimage for ArchiCAD. They can improve the functionalities of the original programs, for example, as the recognition of the points as snaps. Given the fact that BIM is a platform, and not a single software, it is impossible to have one unique program that solve all the matters (Achille et al., 2015).

4.2 Materials identification

In general, it is not possible to do the material identification only with visual inspection. In order to obtain the fundamental material properties of each structural element, some experimental tests have to be done. Therefore, to properly assess the correct behaviour of existing buildings, as well as to verify their safety for use or to withstand seismic vents, it is fundamental to know the nature and the mechanical properties of these materials, acquired with methodical and destructive technologies (destructive tests) and non-destructive or minor destructive ones (NDT/MDT).

Mainly, there is lack of knowledge of the ancient material and construction methods and techniques. They are very important to understand the behaviour of the historic structure to help in the conservation and maintenance of the proper monument. In the past, they used materials that nowadays are not available, so for the restoration it is important the respect of the original materials, protection of the heritage values and respect for authenticity. All existing documentation is needed for finding out more information regarding the cultural heritage.

Anyway, it cannot be reached a complete knowledge of the ancient materials, but the information obtained about the mechanical and physical properties should be implemented in the model (Figure 17). In the databases of all available BIM programs can be found mostly data relevant to modern materials and not ancient ones (Achille et al., 2015).

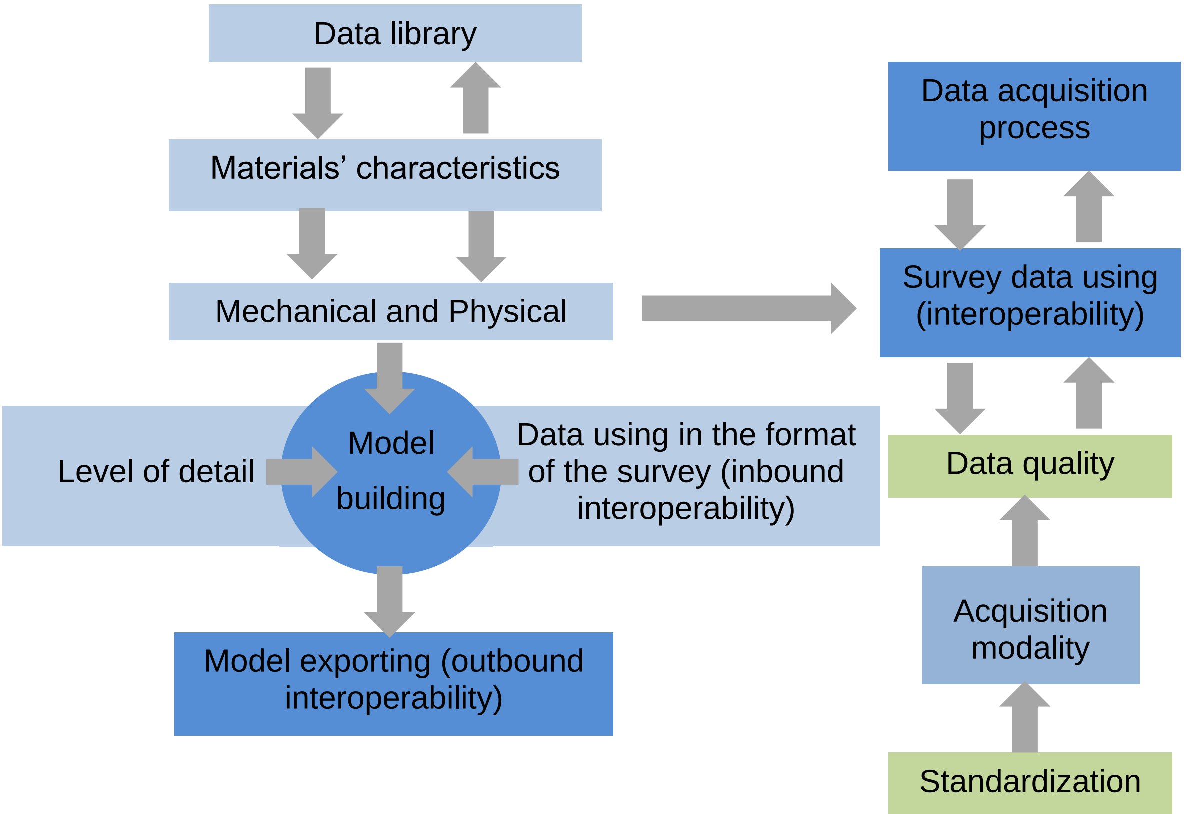


Figure 17 - Workflow of the management of the data related to the BIM model of the historic building (Achille et al., 2015).

Many research studies have been developed around the subject of BIM for historical documentation (Logothetis et al., 2015) where full 3D models of some heritage structures. In this study, some of them are going to be mentioned to explain the procedure, the technologies used, the difficulties and challenges that had to be overcome and the final results obtained.

4.3 Application of HBIM in some case studies

In the study from Dore and Murphy (2012) is being shown the application of HBIM and CityGML for modelling and analysing a heritage construction site. A model of the Georgian street from the 18th century, located in Dublin, Ireland, was created. The street known as Henrietta Street is one of the earliest Georgian streets in Dublin and is of great historical significance (Figure 18). All the buildings show great classical style architecture. During the 19th and 20th century the street fell into disrepair and, despite some recent restoration work done, there are still a couple of buildings that need urgent attention.

Figure 18 - Henrietta Street (Dore and Murphy, 2012).

The geometry survey process was done with laser scanning and image acquisition methods. The final orthographic images were imported into the BIM platform ArchiCAD. The use of laser scanning and photogrammetry can record very high and accurate levels of detail, which is very important for cultural heritage (Dore and Murphy, 2012).

Figure 19 - Registration of first three scans (Dore and Murphy, 2012).

To ensure the accurate registration of the results during processing, five to eight common targets were surveyed. The final products included segmented point clouds, orthographic imagery, cut sections, elevations and plans. With the use of the software ArchiCAD as a BIM application was implemented also the HBIM process. The first phase included the modelling of the walls from the data obtained from the laser scanner (Figure 20). Next the modelling was completed by combining all the required library parts such as windows, doors, columns and all other building elements. All parameters for the library objects were measured from the geometry survey data and were applied to the library part before mapping. At this stage, further attributes such as function, class, year of construction and some description to the 3D heritage model (Logothetis et al., 2015) can be added if known.

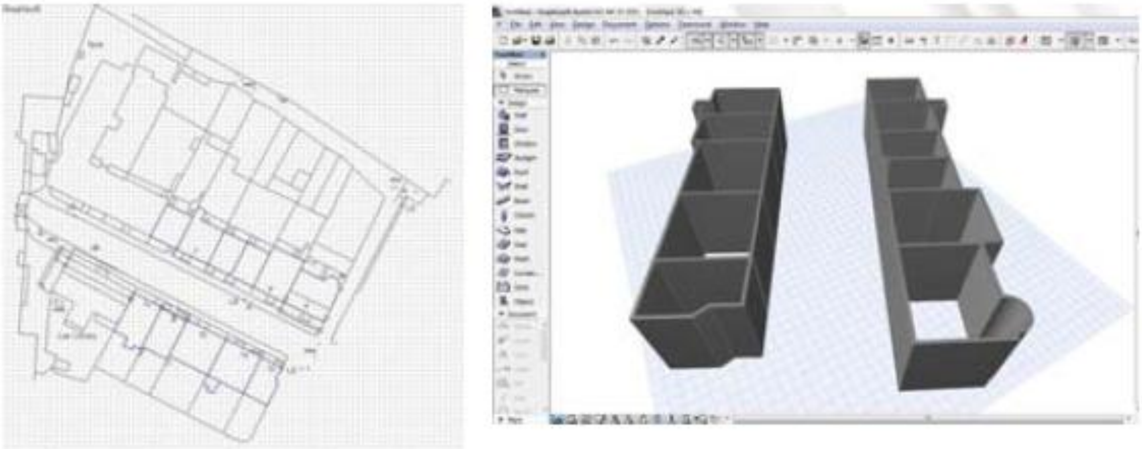


Figure 20 - Modelling of the walls (Dore and Murphy, 2012).

In this way, the model of each building was completed by combining all the different parts. The Geometric Descriptive Language (GDL) was used for the modelling of the windows and other specific elements. The road and footpaths were modelled as mesh models derived directly from the laser scan points. The final HBIM model can be seen in Figure 21.

Figure 21 - Final HBIM model for Henrietta Street (Dore and Murphy, 2012).

The final stage is converting the HBIM model (Figure 22) for Henrietta Street into CityGML for further GIS analysis and efficient management that is required for maintaining urban cultural heritage monuments (Dore and Murphy, 2012).

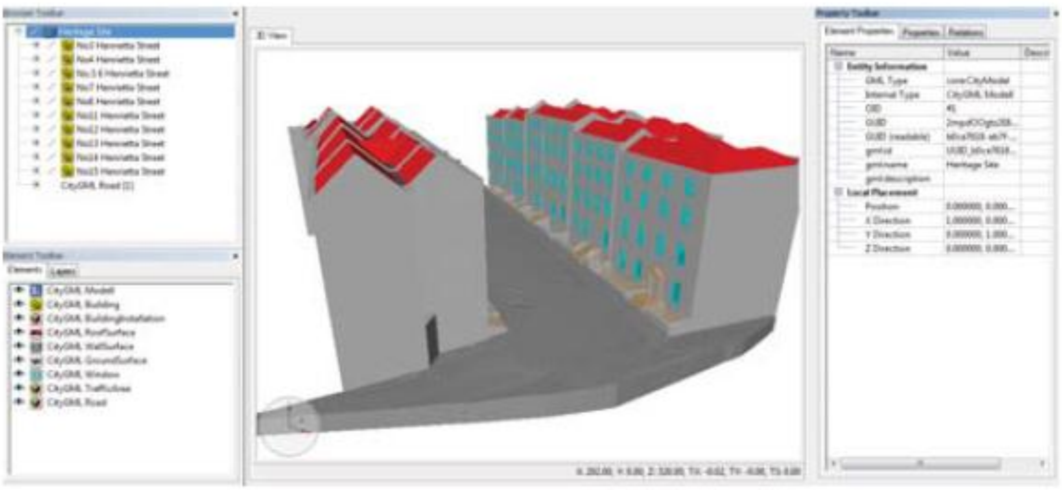


Figure 22 - Final model with software CityGML (Logothetis et al., 2015).

Nevertheless, there were some problems for heritage application, such as that the current feature classes and semantics were not detailed enough to describe the architectural details. This means that, for now, complex shapes must be developed separately from the process of building construction.

Another research for heritage building is the Batawa project-model that includes a redevelopment proposal for approximately 600 hectares of land including a former factory in Toronto (a cluster of three 19th century heritage buildings) with its rich history of modern architecture and town planning (Fai et al., 2011). The goal of this study in the documentation of the heritage assets of Batawa is to develop a BIM model using available software packages that are appropriate for specific applications

(AutoCAD, Civil 3D, SketchUp, Revit,) (Logothetis et al., 2015). This model will serves as a digital archive to help in conserving the extant heritage buildings and planning and to test future development proposals within the context of these historic buildings and plans (Fai et al., 2011).

In general, their approach for the modelling of the Batawa buildings includes laser scanner, photographs, blue prints and on-site visual inspections. They used the existing drawings from the project as the starting point since existing workflows for leveraging point cloud data was still in its infant stages. BIM was used as a platform to incorporate all the information regarding the structural elements, materials and construction (Figure 23), instead of only focusing on the geometrical survey of the heritage buildings (Fai et al., 2011).

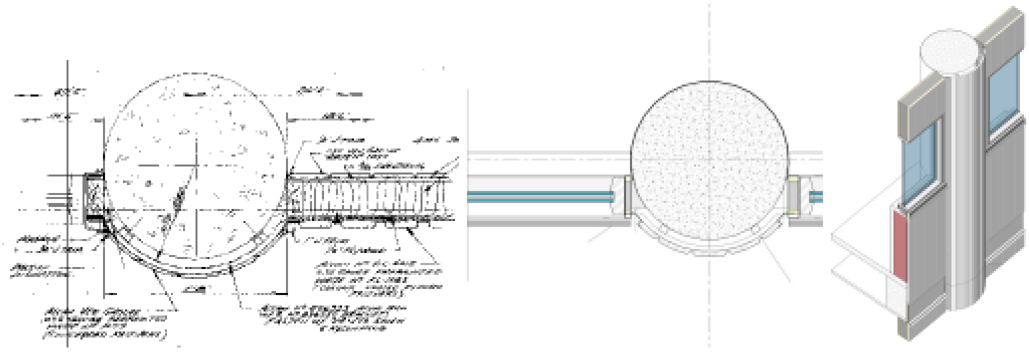


Figure 23 - Original drawing plan (left) and reconstruction in Revit (right) (Fai et al., 2011).

To achieve all of the above, heterogeneous data was used to create the model. The Batawa project brings together different datasets into a single digital object that allows access to, and on-going verification of the individual assets that comprise the integrated model. The model uses point cloud data acquired through terrestrial laser scanning. Furthermore, it was included data related to the type of the building, performance and construction, as well as material typically associated with intangible heritage such as storytelling and music. Finally, to bring it all together into a single model, a robust project management tool was used (Navisworks) to incorporate the diverse software required for the project (Logothetis et al., 2015).

Figure 24 - Final HBIM model of the factory (Fai et al., 2011).

The 3D HBIM model (Figure 24) was created in order to manage and maintain the factory with all the other structures. This way they examined the model at both micro and macro scales with no loss of reliability or data. Additionally, intangible heritage information was incorporated, such as historical images and texts, multi-language storytelling, and music (Logothetis et al., 2015). The purpose with the Batawa Model is to have all the current verifiable historical and projective information in one place, one model, so that if any of the facts are not correct they can integrate new materials and new information without having to be completely rebuilt. Even though the Batawa Model is not entirelly parametric, it has a great advantage for the parametric relationships between all data types for heritage documentation. It may well be the most significant contribution of this technology to the field of heritage documentation, as the ability to reveal time-based parametric relationships between tangible and intangible heritage assets. Finally, the Batawa Model can be viewed trans-temporally by employing the timeline function of the project management software (Fai et al., 2011).

Therefore, this review of these two case studies in the field of cultural heritage with the use of the current BIM applications shows the diversity and complexity of the BIM technology in different fields, buildings, monuments, and environment. Most researchers adopt a similar approach and methodology of using a laser scanner or photogrammetry for the geometry description of the existing building, and use any available source (onsite inspections, historic and architectural books) for the identification of structural details and materials. All the database of parametric historic objects is created and incorporated into the 3D virtual model of the historic building, as well as additional details about the various objects such as construction materials, schedules for cost decay, energy etc. adding intelligent data to the geometric model. Many developments and changes have occurred in the last years in BIM, and there is still a lot of space for many more to be accomplished (Logothetis et al., 2015).

In the case study from Achille et al., 2015, they studied different BIM platforms and concluded that the model cannot contain all the information that it should have. Therefore, it is needed some help from an external modeller, in order to achieve a sufficient level of detail. Even if it is possible to model the building, and implement some information inside it, there is not yet a complete level of interoperability,

Ultimately, although there are several technologies that help BIM software to model historical buildings, the applications need to be perfected and shaped for the needs of a heritage structure. BIM process is in progress and it is directed towards the heritage world (Achille et al., 2015).

5. BIM SOFTWARE USED FOR THE CASE STUDY

5.1 ArchiCAD

Graphisoft develops Building Information Modelling software platform for architects, designers and planners. In 1987 was introduced the company's flagship product called ArchiCAD - an architectural design software (Graphisoft, 2017).

ArchiCAD was firstly introduced as the Virtual Building concept and later in 2003, regarded as Building Information Modelling (BIM). It is a complex architectural design tool which allows designers to draw walls, slabs, beams and other structural elements and objects, also offering 2D and 3D drafting, visualisation and documentation functions. The modelling of the objects can be achieved through using standard parametric of structure elements. By creating a three-dimensional model and detailed technical documentation, it enables architects to use ArchiCAD from the earliest design phases to the technical detail drawings (Graphisoft, 2017).

ArchiCAD is a BIM software solution for the architectural and engineering industry that thinks and works in a similar manner as designers. All creative work and design documentation happens in 3D, so it can be obtained results in a project's real 3D environment. There are several kinds of computer models that can be used such as conceptual, visualisation, BIM, construction coordination, site plan and structural design models (Figure 25) (Graphisoft, 2015).

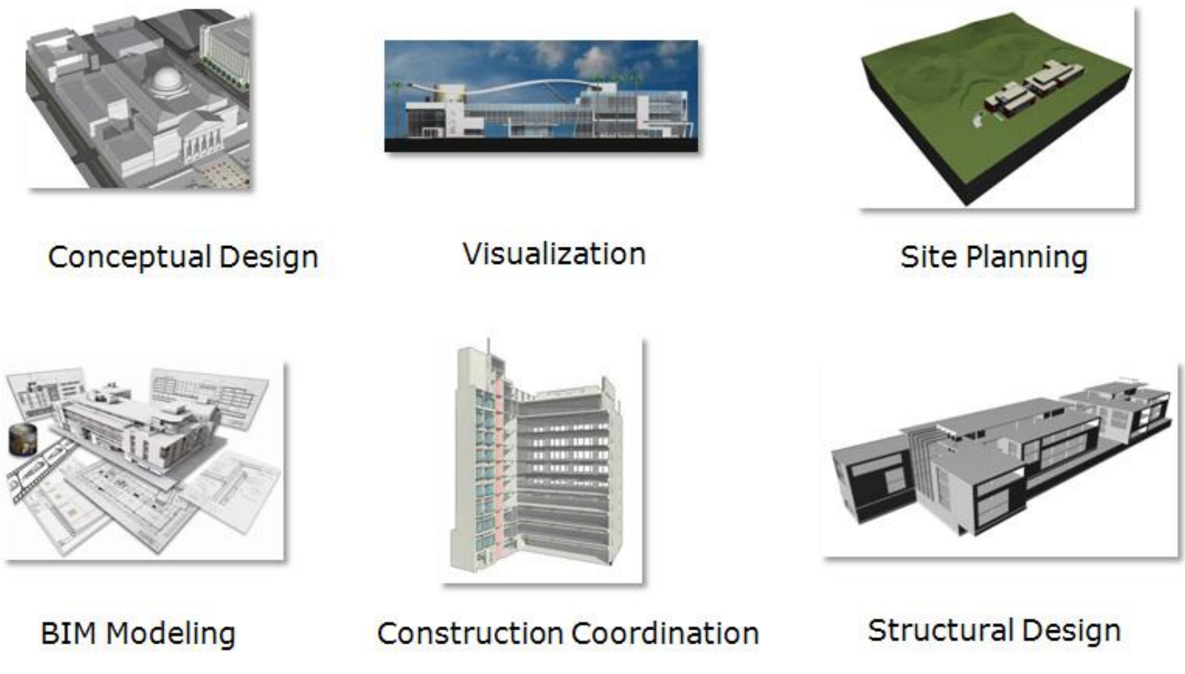


Figure 25 - Different kind of computer models (Graphisoft, 2015).

Building views, sections, elevations, interior elevations and 3D documents are all derived from the Building Information Model and with every change are updated automatically (Figure 26).

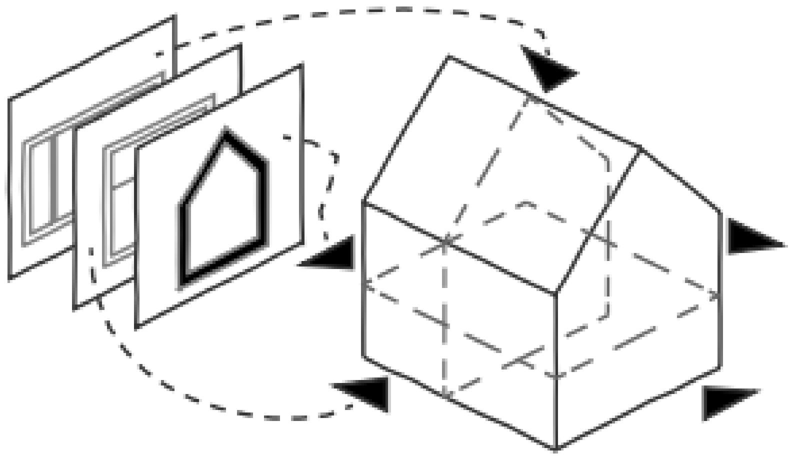


Figure 26 – Automatic documentation (Graphisoft, 2016).

ArchiCAD offers a native BIM design and documentation workflow for Renovation and Refurbishment projects common in developing parts of the world. Hence, this program has powerful view setting possibilities and endures unique drawing and modelling. Having integrated publishing capabilities, ensures that printing or saving the various drawing sets of a project will not require extra time and will be derived from the same Building Information Model (Graphisoft, 2017).

The modelling of the objects in ArchiCAD can be achieved through using standard parametric construction elements. Each element shape can be done easily and changed in the most appropriate view. while intuitive tools help to create conceptual models by combining the creative freedom with the well-known efficiency of its robust Building Information Model. A comprehensive set of tools supports the creative process of every different and new shape within the context of the project (Graphisoft, 2016).

One of the most used tools for creation of custom objects and elements is the MORPH tool. It has no geometric limitation and helps with the direct modelling capabilities of the BIM design in order to create free form elements without the need to imports special shapes from other programs. Compared to traditional construction elements, the Morph has practically no geometric limits because every edge, point and surface can be moved and shaped freely and textures can be fine-tuned on every surface (Graphisoft, 2017).

Morph elements consist of one or more sub-elements which can include faces and/or edges. For any Morph, it can be edited the entire element as a whole, or any of its sub-elements separately, or in combination. They are full-fledged components that appear in all the software's views and can be classified. As for other 3D elements, also for the Morphs, materials properties and textures can be applied on the elements. In the IFC properties it can be described its structural function as well as every other property that can be implemented for the other elements (Graphisoft, 2017).

This tool is a complete solution for creating custom shapes of any type. The shell tool also enriches all architectural forms possible even for existing historical building. They both allow from the beginning of the design process the model to be as accurate as possible in reality (Figure 27) (Graphisoft, 2017).

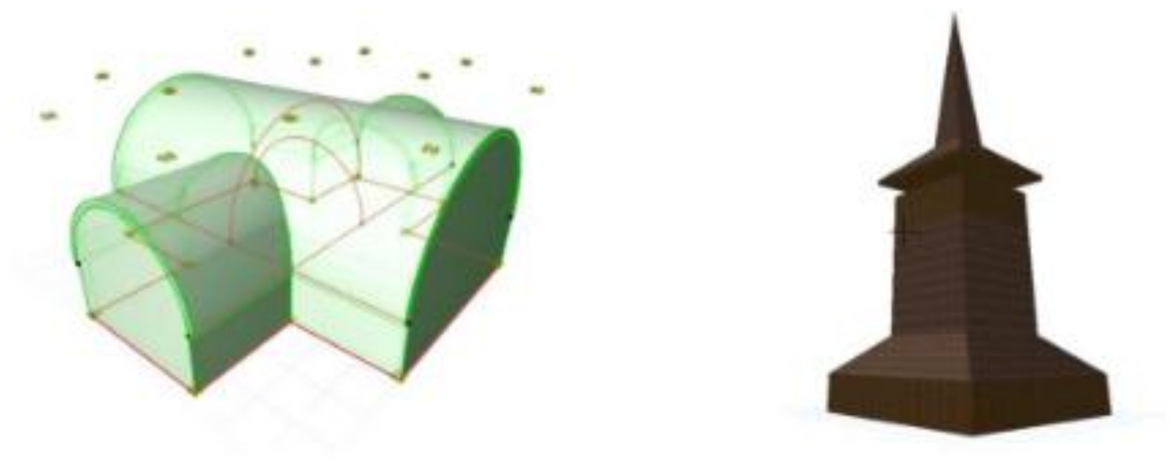


Figure 27 - Use of shell and morph tool (Graphisoft, 2017).

ArchiCAD enhances new priority-based junctions and intelligent building materials which ensure a correct graphical representation of all the structural elements and materials in sections-cut fills, surfaces in 3D views and thermal properties. It is used mostly for design and construction of new building and that is why Graphisoft continues to innovate in the green environment, by offering the best workflow for sustainable design (Graphisoft, 2017).

The best reward for a passionate architect or designer is to see design ideas take on physical form. Therefore, BIMobject as a part of ArchiCAD provides more than a thousand real, up-to-date manufacturer specific objects and other generic building components which help to make the model more real (Graphisoft, 2017).

ArchiCAD is a founder of the OPEN BIM approach to collaborative design, construction and operation of buildings based on open standards and workflows. The "I" which stands for Information in BIM is the most important part of this application. It offers structural collaboration with an optimize workflow by sharing only relevant information about load-bearing structures (Graphisoft, 2016).

Building information modelling enables to implement all the possible information collected into the 3D BIM model and allows engineers to collect, edit and maintain information about a building from the first sketch, through the building phase and beyond. To design, develop and manage a building is a highly complex process that requires smooth communication and collaboration among all members of the project team. Being able to work at the same time on the same model is dream come true for every designer or architect. They can have meetings with external consultants and engineers which can provide an inestimable asset for the building management and maintenance (Graphisoft, 2017).

Advanced BIM applications offer integrated data communication and data sharing solutions for all project stakeholders. It is such advanced data-sharing technology which will empower sufficiently powerful communication to support this collaborative approach. The AEC industry is moving from a “file-based environment” toward a “data-based environment”. The information stored in the BIM model can be shared in many file formats with external project team members (Figure 28):

•IFC (Industry Foundation Classes)

•DXF-DWG (AutoCAD Drawing)

•PDF (Portable Document Format)

•XML (Extensible Markup Language)

•Other native CAD file formats (Graphisoft, 2015)

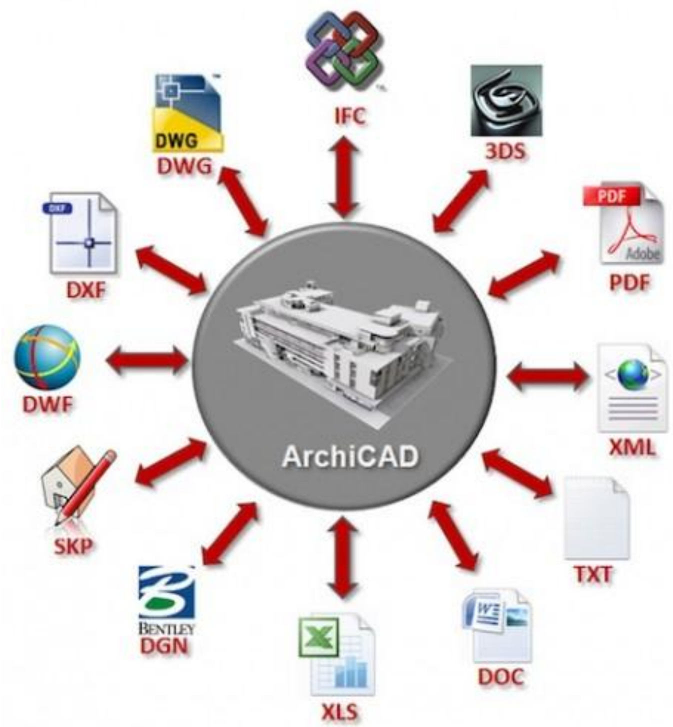


Figure 28 – External collaboration and data sharing (Graphisoft, 2015).

This BIM application is providing with smart tools, updating the design workflow, giving a graphic user interface as a true reflection of the designer and allowing to create, edit and modify the designs in their natural, 3D environment, therefore to make designers life easier.

ArchiCAD is focused on architecture, design and creativity, combined with cutting-edge technology and innovation. It ensures that every design and collaboration tool will serve their needs, form the first sketch throughout the entire life-cycle of the building (Graphisoft, 2017).

5.2 Geometric Description Language (GDL)

Geometric Description Language known as GDL is an embedded functional scripting programming language of ArchiCAD library parts. It has been developed to describe 3D solid objects like doors, windows, furniture, structural elements, stairs, and the 2D symbols representing them on the floor plan.

GDL provides access to modelling of objects through a BASIC like language; these objects are specifically constructed for one or many uses and carry the required parametric information for the object's function. Shapes are scripted, based on primitives that represent the simplest solid objects; these are the building blocks of GDL and culminate to create the more complex parts (Dore et al., 2012). GDL is an open and free standard that can be easily used, so the initial development and maintenance costs are low. Due to its parametric nature, all GDL objects can be easily accessed and managed on the Internet. Moreover, data conversion is automatic, so there is no reason to reproduce data in different formats such as DXF and DWG. All the information can be kept on the website updated, based on the fact that the maintenance of GDL-based electronic product libraries requires little effort (Graphisoft, 2017).

GDL objects are stored in external libraries and they are called library parts in ArchiCAD. Each library part contains several text-based scripts dedicated to different purposes, including 2D symbol, 3D model and description for quantity take-offs. These objects can have multiple purposes such as:

- fulfilling custom requests;
- creating columns, statues and details for heritage structures;
- creating manufacturer object collection which is based on specifications;
- creating a standard object collection for office use;
- customizing, enhancing objects shipped with ArchiCAD (Graphisoft, 2012).

It was created to encourage designers and architects to build their own geometric objects by using this language. The use of GDL allows the creation of any number of rich parametric BIM objects and for their storage in internal libraries or databases for further reuse or modification (Murphy et al., 2011). In this way they can extend the possibilities of design and presentation by creating their own GDL objects. This can be used to produce elements not present in standard libraries or to define specific complex elements. The representation of each element can be done with different levels of detail (LOD) depending of what is needed for the model (Figure 29) (Graphisoft, 2012).

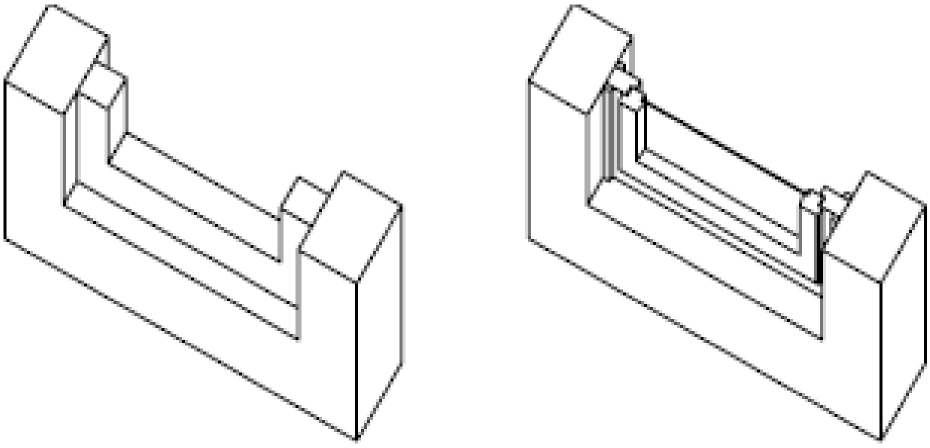


Figure 29 - Window representations with different levels of sophistication (Graphisoft, 2012).

This language can be used by anyone with the affinity of programming for creating some simple objects to more complex ones. First, it has to be defined a certain way of thinking when it comes to solving a geometric problem in GDL and to get familiar with the options and commands for 2D and 3D representation in a user-friendly parametric programming environment. There is variety of available 2D drawing tools and basic 3D shapes that can be used for creating the particular object. By simply placing and combining them, or using solid element operations can lead to modelling different objects such as doors, windows, stirs, furniture and many more (Figure 30).

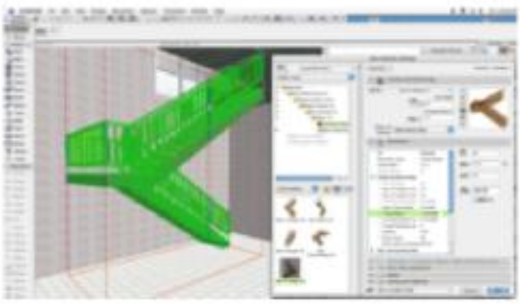


Figure 30 - Objects created with GDL (Graphisoft, 2015).

Using GDL has many advantages not only for BIM users but for all participants of the AEC industry. It gives flexibility and control with its ability to export product data in common CAD file formats, including

DXF, DWG, C4D, 3DS, and the emerging industry standard IFC. Also provides integration with the building design of the components which benefits both the designer, who will use the real-life objects in their design, along with the component manufacturers, using the advantage of successfully market their products in an earlier stage of the design process. All manufacturers' data are included in the GDL object information, which are available to the designer, the facilities manager and all other building professionals who need the access of the product specific information throughout the building's life cycle (Graphisoft, 2015).

All heritage buildings have complex decorations and details which are not built in the present day as well as different typologies of walls, slabs and columns. In the structural elements available in most BIM applications, one cannot find any of those specific elements. Therefore, by using the GDL, these elements can be modelled and saved in the library of parametric objects which can be used for the future HBIM projects.

For example in the study from Dore et al. (2012), creating parametric libraries by modelling elements from a heritage building is explained by using GDL. Some columns are made up of decoration in the form of mouldings which are combined with cylindrical and planer objects and are brought together, based on a series of rules in relation to space, geometry and aesthetics to create a whole structure. From designing of small parts as parametric mouldings, followed by the parametric design of elements such as columns, pediments, walls, windows, roofs etc. a design framework based on parametric design and shape rules is presented (Figure 31).

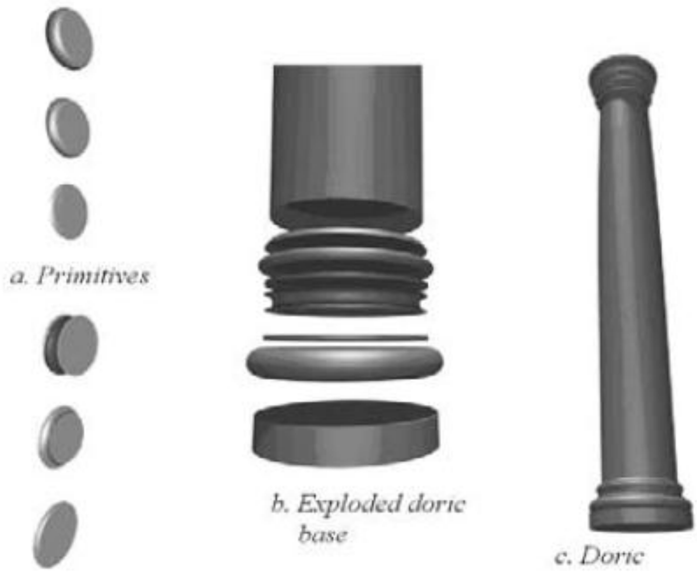


Figure 31 – Combined primitives for Doric columns (Dore et al., 2012).

The research from Murphy et al. (2011) describes and confirms how the GDL can be implemented in the HBIM, such as scripting some of the architectural elements. In this study, the design and detail for the parametric objects are based on architectural manuscripts ranging from Vitruvius to Palladio to the architectural pattern books of the 18th century.

The architecture from this period of cultural heritage has presented and documented some scientific rules for the creation and construction of the architectural elements. By using the historic data available for the specific heritage building, enables the designers to develop in detail the structural elements with taking into account the methods of their construction and the material properties (Murphy et al., 2011).

Therefore, with the use of GDL and documentation from historic sources, a library of parametric objects can be easily created. A historic framework for building a parametric library of architectural elements is proposed, through assessing the evolution of architectural manuscripts in order to map and identify significant rules that represent a wide range of classical buildings, and can be applied to computer modelling. Furthermore, the interpretation and understanding of those historic rules is fundamental and can be more easily adapted from architectural pattern books and papers which rose after the renaissance period. These patterns are interpreted for both geometric shapes and non-uniform shapes (Murphy et al., 2011).

Additionally, using GDL it is possible to add some other parameters that can be used, for example, to edit the position of the window openings that do not have the same dimensions as the survey data within HBIM either in 2D or in 3D. In general, this is necessary as all heritage buildings would not have the same proportions or dimensions. Considering different historic periods, each structure had different construction methods and architectural elements. However by first modelling an 'ideal' façade the process of combining library part will be much quicker and easier. The perfect façade would be able to be overlaid with scan data such as orthographic imagery and if the position of the window openings does not coordinate with the survey data, it could be easily modified as seen in Figure 32 (Dore et al., 2012).

Figure 32 - Interactively modifying position of window openings (Dore et al., 2012).

ArchiCAD software dissolves parametric objects into built construction elements (walls, columns, beams, shells etc.) and GDL objects which can be created within a three-dimensional space that is measured by the x, y, and z-axes. The position, orientation and scale of objects are prepared by the global origin and local coordinate system (Murphy et al., 2013). Those objects programmed with GDL are particularly created for one or many uses and can contain the required parametric information for the object's function.

All the shapes are scripted, based on primitives that represent the simplest solid objects. They are stored in the computer memory in binary format, and the 3D engine generates them within 3D space. Combining those shapes, which represent the building blocks of GDL, can be created more complex elements and stored in the parametric library of objects. The primitives are made up of all the vertices of the object's parts, as well as all the edges linking the vertices and all the surface polygons within the edges. The primitives are assembled together in groups known as bodies and these bodies created the 3D model (Murphy et al., 2013).

The shape commands and new library of primitives allow for all configurations of the classical orders in relation to uniform geometry. GDL develops non-uniform and organic shapes through a series of procedures attempting to maximise the parametric content of the objects (Figure 33 and Figure 34) (Murphy et al., 2013). Furthermore, it can be created a range of distinct shapes for the modelling of some of the structural elements or details for example on the façade, base of the columns etc. All shapes and parts of the elements are stored as individual parametric objects or can be combined to make larger objects in a library and when used in a HBIM model can be modified and deformed to match their particular requirements. The goal will be to create more parametric objects that in the future can be used in the modelling of different historic buildings.

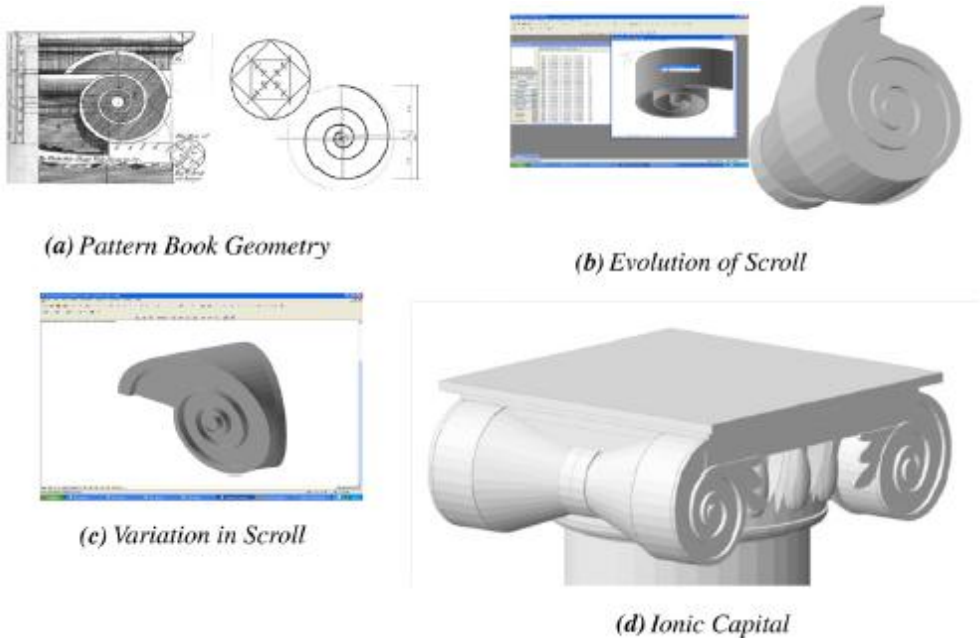


Figure 33 – Ionic capital (Murphy et al., 2013).

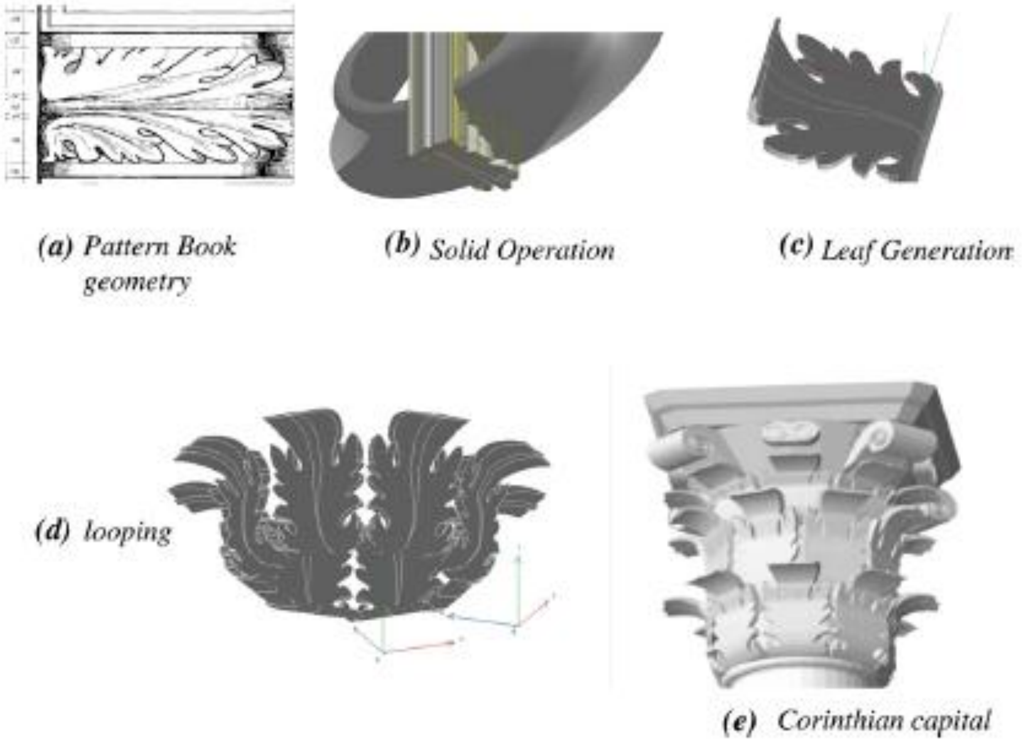


Figure 34 – Corinthian column (Murphy et al., 2013).

GDL has been developed for the program ArchiCAD describe 2D and 3D elements in a user-friendly parametric programming environment. The language itself is continually being improved and upgraded, but also finds a way to keep the compatibility intact as much as could be expected. Therefore, the GDL developers have a challenge to satisfy all the criterions regarding the progressions given by ArchiCAD for some new features and also the compatibility which constrains them to keep the old command as well as the new ones (Graphisoft, 2015).

6. CASE STUDY: MANAGEMENT OF AN HISTORIC CHURCH

Historic structures preserve many values involving different aspects from cultural to economic resources. Important international documents such as ICOMOS/ISCARSAH have been developed during the past years in order to protect the cultural heritage. The scientific approach proposed by ICOMOS describes the role of historical research, inspection, monitoring, modelling by structural analysis, and safety evaluation. As a historic structure, the Church of São Vicente is an important element of the city of Braga, Portugal.

The case study will be partially based on the report done former students of the SACH Master (Betzer et al., 2014). The aim of this work was to study the structural behaviour of the church of São Vicente and to propose possible needed interventions after characterizing its damage state. At the beginning, a historical survey and visual inspection of the church was carry out and information about geometry and material was obtained, From this analysis, it was possible to define possible causes of damage, which were further investigated with the use of NDT and MDT methods, as well as monitoring, to complete the knowledge of the building. Finally, some interventions were proposed to maintain this heritage building, namely, the replacement of the roof system, which was leaking.

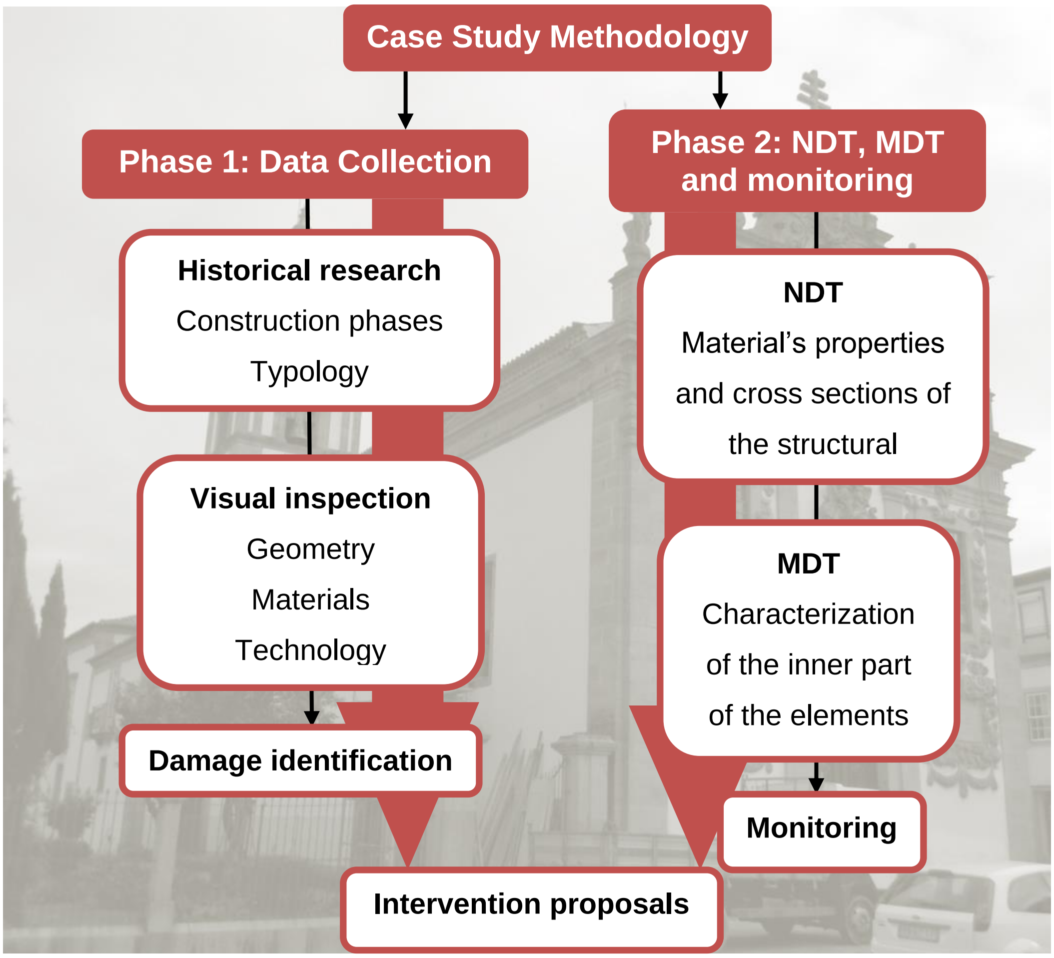


Figure 35 - Case study methodology (Betzer et al., 2014).

6.1 Historical research about the Church of São Vicente in Braga

Baroque architecture in Portugal (XVII-XIX) had great longevity, beside the development of Mannerist style. These two ways of producing Portuguese baroque architecture persist until the late eighteenth century in different cities, including Braga. The religious architecture in the city of Braga and the geographical area of influence has unique typological characteristics such as centred plan and external configuration, rear bell tower and barrel vault with ribs (Betzer et al., 2014).

Most of the historic buildings in Braga are with made of symmetric plants. Their exterior is usually covered by white plaster with a frame of granite stones around the openings and in the corners. Between the 17th and 18th centuries, the localization of the bell tower was in the back part of the church. Many churches from this period have a barrel vault composed of granite ribs covering the main nave. The decoration of the vault is generally focused on the panels between the ribs (Betzer et al., 2014).

The church of São Vicente, also referred to as the Parish Church of São Vicente, is located in the north of Braga. The historical building covers a triangular size area between the street of São Vicente and the street of Conselheiro S. Januàrio, as shown in Figure 36. It is an important example of Baroque architecture in the city and in the country. Therefore, it was declared as an historical building of public awareness in 1986 (Património cultural, 2017).

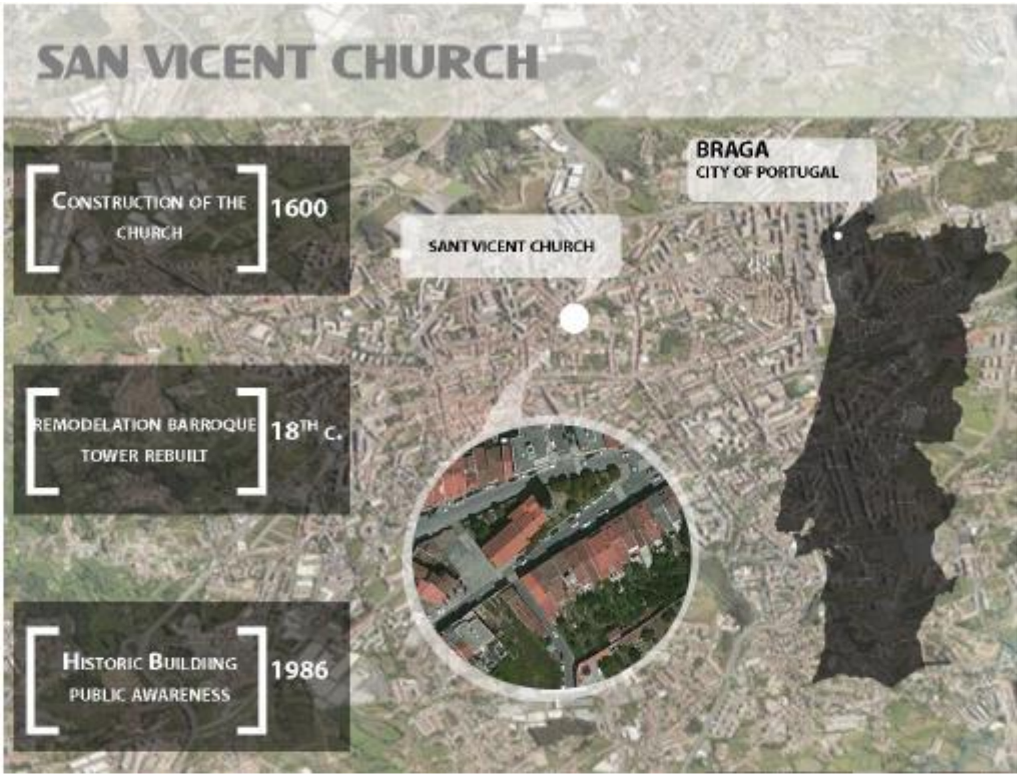


Figure 36 – Location of church São Vicente (Betzer et al., 2014).

Despite the historical importance of the church for the neighbourhood, hardly any historical documentation related to the phases and eventual changes that occurred during the construction and use are available.

In the Proto-Baroque and Baroque work of the church of São Vicente, some of the most prestigious architects of the city of Braga intervened, which, over different generations, contributed not only to the building, but also to the risk of the altarpieces and the organ. These names, which were of the greatest importance in the development of the new Bracara Augusta under the aegis of Archbishops D. Rodrigo de Moura Teles and D. Gaspar de S. Vicente, are: Manuel Fernandes da Silva, André Soares and Carlos Amarante. The church itself, located in an area quite far from the historic centre, contributed decisively to the development of the area around it, functioning as an urban centre around which part of the city was structured (Património cultural, 2017).

However, the history of this church begins much earlier. It seems that exist some evidence of a primitive temple, at least since the 7th century, as a funerary tombstone of the Visigoth era. This headstone, located in the sacristy, is dated from 618 let us understand the possible existence of a primitive hermitage situated northward compared to the actual church, in a place called Infidias. In this headstone is the first connection to the day of the week ‘Monday’ as the Christian Portuguese name ‘Segunda feria’ (Figure 37). Subsequently, the first reference to a temple dedicated to São Vicente appears in 656, as wrote in the façade headstone (Betzer et al., 2014).

Figure 37 - Headstone in the sacristy (Betzer et al., 2014).

Until this moment, the main altar was not included in the composition of the church. Unfortunately, this first chapel was, apparently, destroyed by the Arabs invasions and was remodelled in 1565 and then reformed again in 1691.

No drawings are available about the project of this church that in 1683 the government wanted to remodel and enlarge in the main altar area, saying that the church was in bad conditions and unsafe and there was not enough space for religious celebrations.

In fact, the work began earlier, since in 1686 the Brotherhood intended to rebuild the church, especially the main chapel, following the model of the church of Nossa Senhora a Branca. However, this plan did not materialize, and the work began only in May 1689, with a project by Domingos

Moreira. Afterwards, the work continued under Manuel Fernandes da Silva who only did the upper part of the façade. These facts were obtained from the documentation available from that period (Património cultural, 2017).

Finally, in 1689, the congregation reached the right economic condition to start the construction of the main altar and, in 1691, the church was already having its current shape. The works finished in 1694 with the vault and the façade.

The façade reveals the transition from Mannerism to Baroque, present in the multiple decorative elements that surround the frames of the spans and in the top, cut off, housing the image of São Vicente (with the attributes of martyrdom and Above the Pontifical Insignia). Two angels make a composition on the sides. On the portal, and at the centre of the interrupted pediment, is the sculptural representation of the Baptism of Christ. The bell tower is located behind the main chapel, to free the facade, in a solution common to other temples (Figure 38) (Betzer et al., 2014).

Figure 38 – Satellite view of the church (Betzer et al., 2014).

Sao Vicente is a baroque church. The facade, with Mannerist elements, is the first building of the Baroque Bracarense. Recalling an altarpiece, the façade, which rises harmoniously, adorned with clearly baroque elements, has been attributed to Frei Luís de S. José, the same that projected the front of the Church of the Monastery of Alcobaça. The image of the patron saint, São Vicente, was tucked up in a niche (Betzer et al., 2014).

The façade presents the classical features typical of the churches in this area, covered by white plaster and with visible shells in granite stones (Figure 39 and Figure 40). The main façade, with Mannerism features, is completed with the statue of São Vicente in granite, set in a niche surmounted by the Papal Cross.

On the crown of the façade, there is a papal cross that recalls the privileges and indulgences that Pope Clement VIII granted to this church around the year 1598 in the time of Archbishop Augustine de Jesus. The construction of the façade lasted for several years and was only completed in 1717, by the great master of works Bracaran Manuel Fernandes da Silva. In the interior of the church, the choir was attributed to Carlos Amarante, the organ was built by the master organist Francisco António Solha in 1769 and the tiles (Azulejos) were produced by the Devesas Ceramic Factory back in the 1873 (Património cultural, 2017).

Figure 39 - Side view of the church.

Figure 40 - Main façade.

The important constructions of the church were made during the XVIII century, where the interior of the church turned into a golden baroque style. In that period, these major interventions were made:

- Constructions of the altarpiece and the major altar in the 1721 by the sculptor Barcelos and the Architect Miguel Coelho. The interior was painted of golden colour by the painter Manuel Furtado de Mendonça;
- The construction of the tower: initially the project was to build the tower in front of the church, then it was decided to build it in the back so that the symmetry of the façade could be maintained;
- Covering of the walls of the main altar with tiles;
- The construction of the chorus;
- The construction of lateral altars in the transept.

The bell tower was the tallest building in the city when it was built and therefore it suffered two lightning in thunderstorms. Due to this, it had to be rebuilt twice, the first time in 1750 and then in 1812. Until the mid-1970s the tower was crowned by a majestic weathervane. From its construction, it has been seen as an iconic symbol for the citizens of the city, because it is one of the tallest towers in Braga with a height of 32 meters (Figure 41) (Betzer et al., 2014).

Figure 41 - Bell tower.

All the other parts of the church were covered by tiles in 1873. There are many different ceramics used in the covering of the walls in the entire church. The ceramic used at the major chapel is the oldest one. All these tiles give us information regarding elements with symbolism which are of blue, ochre and white colour. Therefore, they represent the life of São Vicente just before his martyrdom. On the other hand, the rest of the church just has blue and white ceramic, which both are shinier than the ceramics of the chapel. These elements came from another fabric (Gaia Fabric), and represent the martyrdom, death and repartition of the rests (Betzer et al., 2014).

During the investigation about the interventions on the structure, no document was found apart from very recent information. The only intervention known on the building, in fact, is a rehabilitation of the roof structure that took place around 15 years ago. In that occasion, a layer of asphaltic sheet and new roofing tiles were positioned (Betzer et al., 2014).

Another later intervention on the building must have been the application of cement plaster in the façades as well as the closing of some old cracks with mortar, maybe of the same quality.

a. b.

Figure 42 – a. View from the bottom of the bell area (addition of a steal tie); b. Tie beam found in the north area of the church (Betzer et al., 2014).

Other evidence of later addictions can be found in the top of the tower and in the administrative part of the building. Over the bell area of the tower, where the section reduces to a thin hexagonal shape peak, two ties are visible throughout the dust caused by biological attack.

The only room in the top of the north wing from which part of the timber roof structure is accessible shows the presence of a metallic tie (Figure 42).From the external part, it is not possible to detect the presence of the other extremity of the tie and also it was not possible to identify the damage pattern that could have needed this intervention (Betzer et al., 2014).

6.2 Visual inspection

For the study of the church of São Vicente, it was done a documental survey about the history and architecture of the church and also a detailed visual inspection was performed in order to check and confirm the geometry of the structure, the construction materials and the technology that characterize them. Furthermore, a photographic survey was done for the entire church with all the opening and structural changes (Betzer et al., 2014).

The report aimed to analyse the current conditions of the church and to assess its safety. Additionally, it was done detailed damage identification for the church. They proposed and carried out some NDT and MDT techniques to help with the determination of some of the mechanical properties of the materials. It was also proposed some monitoring for better understanding of the behaviour of the heritage building along the years. Some preliminary calculations were performed to assess the safety of the structure and, finally, some recommendations were proposed to improve the performance of the structure.

6.2.1 Geometry

The geometric survey for understanding the architectonical composition of the building was done by using simple tools such as camera, laser tape and meter tape. This allowed the update of available drawings of the church, which seemed to not be completely accurate. In the end, 2D drawings were provided from the floor plan, elevations of the north, south and main façade and one section through the length of the church (Betzer et al., 2014).

In general, the structure was divided in three parts which are the church area, with the altar and chorus, the north wing and the tower (Figure 43). The church area is composed by a principal nave, an altar and a chorus.

Figure 43 - Identification of three main areas of the building (Betzer et al., 2014).

The side main walls with thickness of around 2m, have stairs which are excavated inside them for going up to the two lateral pulpit in the north and south wall and also another similar stairs that are leading up to the main choir in a balcony above the main entrance, where the organ is situated. In general, as typical in the baroque style, openings tend to maintain the symmetry in the two sides, even though some of the doors are closed and are used as altars (Betzer et al., 2014).

The entire main nave and the altar are covered by a barrel vault characterized by granite ribs and a filling panel. Also, the choir space is sustained by a vaulted structure similar to the main one. Inside all historical buildings with baroque architecture like this one there are many wooden elements and decorations on the walls where the smaller chapels are. The main chapel is also made from golden wooden frames as well as the fences of the balconies and the window openings inside the church (Betzer et al., 2014). See Figure 44.

The north wing is the connection between the church and the tower. It is divided into two floors, where is located the office of the priest and some other rooms, most of them used for storage. There is a small room on the second floor which permits access to the roof, which is behind the main altar of the church (Betzer et al., 2014).

a. b. c.

Figure 44 - Inside view of the church: a. View from the entrance; b. View from the main altar c. Stair in the thickness of the wall (Betzer et al., 2014).

The last part of the church is the bell tower, which seems to be completely abandoned and not frequently maintained, apart from the use of the bells. It has several floors constructed in differed periods and with different technologies connected with a granite staircase. The stairs are supported by the granite walls as a cantilever and have wooden fences (Betzer et al., 2014).

6.2.2 Materials

Different kinds of materials were used in the construction of the church of São Vicente, such as granite, cement plaster, stones, and wood (Figure 45). The walls of the church are made of granite and they are covered on the exterior side with cement plaster and painted with white colour and on the internal side with blue tiles painted with different shapes which are called 'Azulejos' in Portugal. The corners of the openings are exposed on both sides and the granite stones can be seen. The floors in the church area are from timber. Also many of the decorations and details typical from the baroque period were made of timber and are non-structural (Betzer et al., 2014).

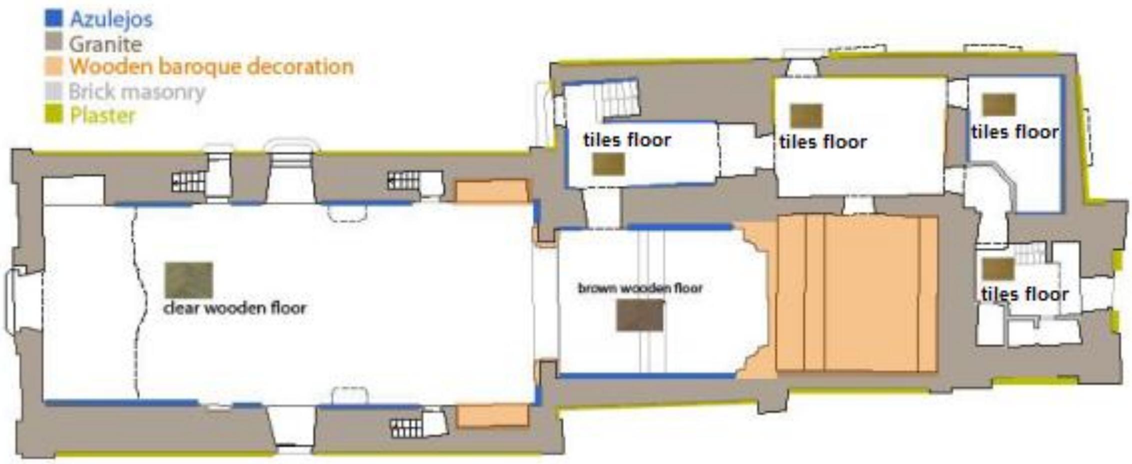


Figure 45 - Different materials present in the structure (Betzer et al., 2014).

The barrel vault was constructed with granite ribs with a visible thickness of 20cm, with a decorated cover panel, which composition was difficult to identify. It seems to be some kind of mortar, due to the fact it is extremely deteriorated form moisture and has many cracks. Further investigation of the vault is definitely needed to confirm, or not, all of the assumptions, since it is an important structural part of the historical building (Betzer et al., 2014).

Moreover, the north wing is composed by granite walls covered externally and internally by plaster and in some parts of the internal walls with tiles. In this part, the floor is also covered with ceramic tiles.

The tower has different granite textures and configurations. The walls are around 1.5m thick and from the internal side of them can be seen that the masonry it is not regular and not covered with plaster. On the first level, the walls are made of uncut stones with thick mortar joins; on the second level the stones are of different sizes and in the joins little pieces of stones are placed. The floors are constructed with different materials and it seems from different periods also. The first two floors are concrete slabs and the other three are timber floors. The second floor has circular holes assumed for passing the ropes of the old bells. Above this level, probably after intervention, a floor was removed and it is possible to see on the walls the holes where the beams should have been placed as well as two different types of plaster: a new plaster and an old plaster. The fourth and fifth level has a wooden floor with wooden beam and finally on the top, the floors are made of granite (Betzer et al., 2014).

6.2.3 Technology

The walls, vault and the roof are three elements object of analysis in the report about the church of São Vicente. Regarding the structure of the church, the composition, morphology and technology of these structural elements, it seemed to be the most important elements for understanding the behaviour of the church (Betzer et al., 2014).

The main question was how the walls were composed. In fact, the hypothesis was that the thickness of these elements as well as the presence of the stair inside the width was suggesting a three leaf wall but after the testing phases, it was shown that the two meters wall show a composition of stone without any leave arrangement (Betzer et al., 2014).

After observing the crack pattern identified in the vault, it was necessary to understand which lines were related to the way of construction of the vault and which were instead defining another crack pattern. The construction technology seems to have been performed with almost regular pieces of stone for the central part of each square and cross elements in the connection between the two directions of ribs (Figure 46) (Betzer et al., 2014).

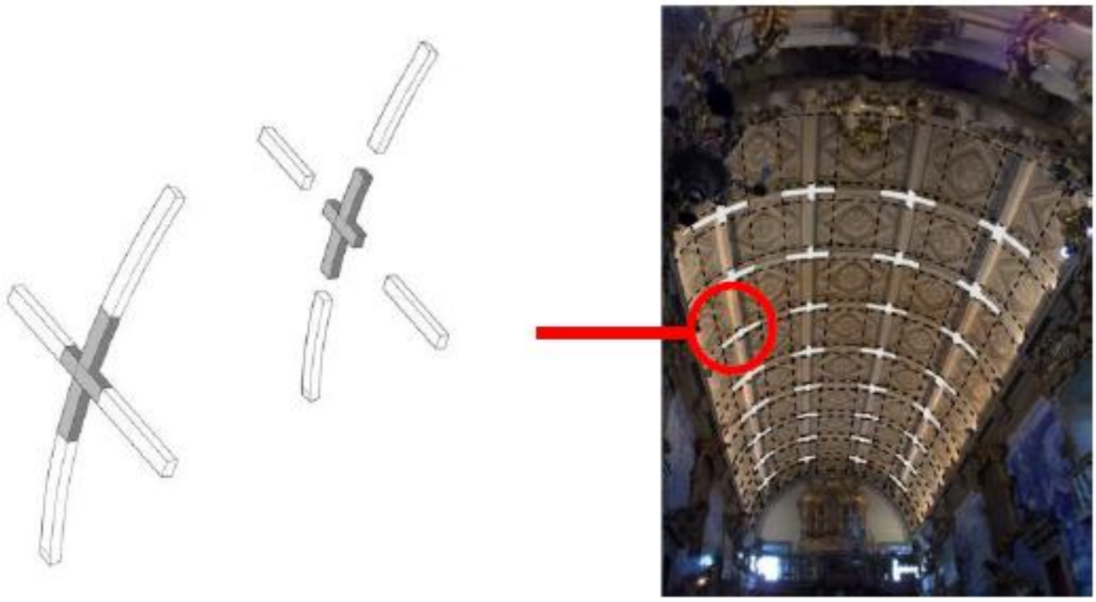


Figure 46 - Structure of the barrel vault (Betzer et al., 2014).

In the upper part of the vault, there is a wooden roof structure. It was impossible to access to this area, however they made some hypothesis supported with photographical surveys made by the architect Francisco Perry Azeredo in 2013 (Figure 47). From his report, it was possible to see the main composition of the roof structure and the last restoration works carried out around 15 years ago. To evaluate the roof structure over the vault from outside and from inside, all the data was referred to the previous visual inspection done by the architect (Betzer et al., 2014).

Figure 47 - Photographic survey on the roof by architect Francisco Perry Azeredo (Betzer et al., 2014).

As it can be seen in the pictures, the tiles are supported by small timber elements that run in the longitudinal direction, which are often detached from the asphaltic sheet that covers the roof structure. Under the asphaltic sheet there is a pressed cardboard that has been cut in the inspection point in order to see the inner part of the roof. In addition, the damaged sheet ends with the principal tiles line, before the gutter, and this generates problems related with infiltration and high water content inside the side walls and the vault of the church (Betzer et al., 2014).

The interior characteristics of the roof are still mostly unknown. From the few pictures taken only few of the trusses were visible. In the image R10 (Figure 46), it seems that the principal rafter and one of the purlins supporting the common rafters are in contact with the vault, but it cannot be known if this happens with all the other elements of the roof.

The connection between the roof structure and the façade is undersized and its design, in which also the asphaltic sheet is not properly shaped, facilitates the access of water and the accumulation of dust that prevent the course of the rain. The presence of an accumulation of debris that generates overloads in the vault and an easier accumulation of dust and water in the sides was noticed from the visual inspection of the roof.

From the previous inspection of the roof it was possible to see also that some parts of the wooden trusses are in contact with the upper part vault. From the few photographs available, it is impossible to define if this phenomenon is local or generally present. The assumption that was made was considering a symmetric deformation of all the trusses of the roof, considering also the uniformity of the tiles. It was considered the possible load generated on the vault system in the north part.

Based on the previous information available, a possible section of the roof was considered as shown in Figure 48. The dimensions of the elements were considered based on the usual sizes and the proportions of the pictures available.

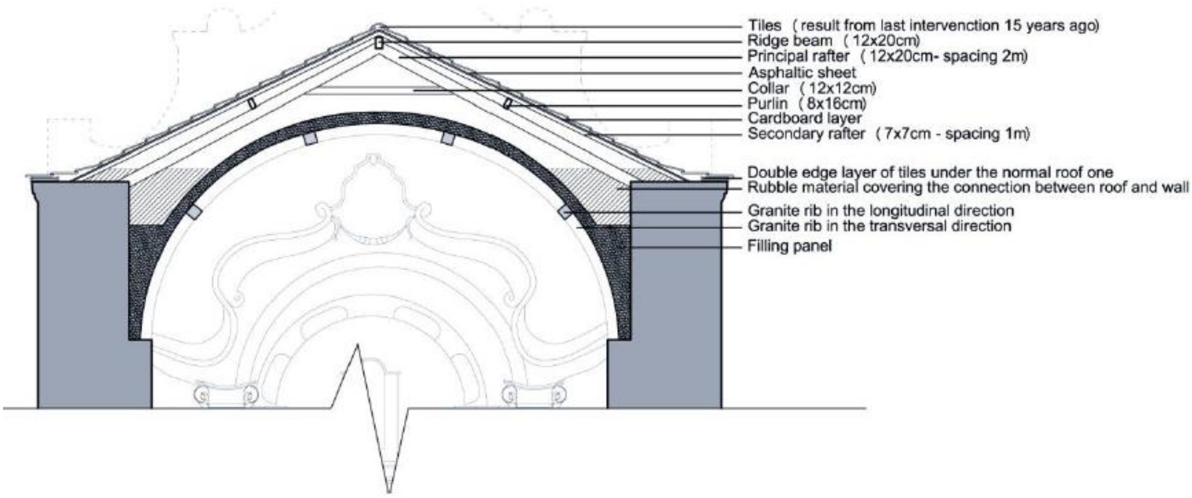


Figure 48 - Section of the wooden roof structure (Betzer et al., 2014).

6.3 Damage identification

The report has given a review also on the damage identification. Tables of damage identification have been done by considering the ICOMOS glossary on decay phenomena, separately for the three areas of the building.

According the identification is concluded that the main problems which affected the church are caused by water, which can be easily seen from all the moisture (Figure 49) present.

a. b. c.

Figure 49 – Damage identification: a. Capillarity rise in the north wall; b. Capillarity rise inside; c. Craquele cracks in the façade of the bell tower (Betzer et al., 2014).

In the covering stone at the perimeter base around all the walls, capillarity rising water can be noticed. Most of all these phenomena can be detected in the north side. Due to its exposition, it affects all the structural elements as well as non-structural. The floor in the outside and in the interior shows exactly the same pathology. In the interior of the church, presence of moisture coming from the roof was detected in the sides of the non-structural panel of the vault, with more important magnitude in the area in contact with the façade. The moisture on the façade can be explained by the problems discovered in roof visual inspection about connection between the roof and the main façade. Additionally, on the two side walls of the lateral façade, moisture and capillarity rise from the gutters can be observed.

The cement plaster, which was probably added after the construction of the church during some intervention, covers all the exterior façade of the building including the bell tower. There were noticed some craquele cracks probably due to the weathering and thermal incompatibility problems.

a. b. c.

Figure 50 - Damages observed on the facade: a. Tilting of the south side wall; b. Cracks in the corner; c. Cracks in the back wall (Betzer et al., 2014).

From a structural point of view the side south wall shows a clear out of plane movement accompanied by several inclined cracks passing through the weakest sections pointing the right pear of the façade.

In the main façade has been observed the presence of significant cracks (more than 4mm) and that is why it was presume the presence of a downward movement of the wall, possibly due to a settlement of the foundations. Also, in the exterior wall that covers the change of high from the main nave to the altar a crack that agrees with this movement can be appreciated (Figure 50).

During the installation of the accelerometers for the dynamic identification, a small movement out of plane in the same direction of the south side wall was easily noticed. As shown in Figure 51 on the north wall it can be observed the difference between the straight line of the tiles coming from the fifteen years old intervention and the underneath masonry stone line. Therefore, this could support the idea that the movement of the walls is no longer active at least since the intervention on the roof. But still some more tests should be done to confirm it.

Figure 51 - North wall view from the main façade (Betzer et al., 2014).

This connection prevents a uniform movement in one side of all the building suffering a significant deformation. In fact, from the previous inspection of the roof, the timber frame seems sliding in south direction as the support is sliding, which causes the contact between the principal rafter and the vault. The movement of the wall together with the load coming from the roof is the main potential cause of the relevant crack pattern that can be appreciated in the barrel vault, as shown in Figure 52. This is due to the sliding of the timber truss that was noticed from the visual inspection of the roof and touching the thin granite vault, which is not a rigid connection between the two lateral façade walls.

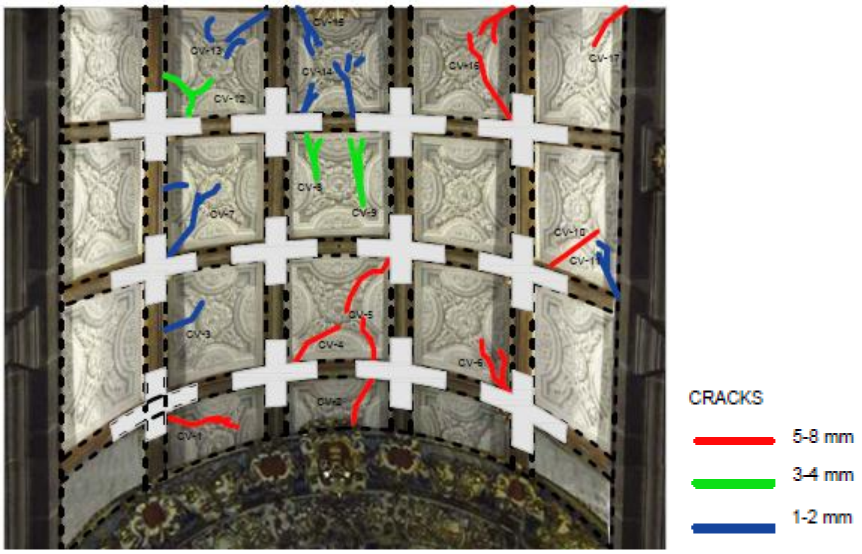


Figure 52 - Damage identification on the barrel vault (Betzer et al., 2014).

6.4 NDT, MDT and monitoring

Several non-destructive and minor destructive tests were carried out to obtain information about some of the mechanical properties of the materials, their composition and morphology, different types of materials, internal voids and irregularities in the historic masonry.

Even though the precision of the methods is low, they are generally used for its non-destructiveness. Hence, it is typically used to confirm a preliminary hypothesis on a larger scale. These initial deductions could be made using minor destructive tests or other inspections. The non-destructive tests that were carried out in the report include GPR and moisture content test.

The information obtained with the GPR test was very important for the analysis. It clarifies many questions about the morphology and technology used in the church, the composition of the walls and the vault. The morphology of the side wall is not characterized by leaves. They are made by granite rock of different sizes interlocked, the stones are fitting together with mortar and the remaining space is filled with smaller stones. In the vault, the GPR tests were performed in the side area, near the main façade, where the choir is located. The presence of moisture was the main opposing in fact, the signal was often absorbed without returning any reading. However it was possible to detect an approximately thickness for the vault of 20cm. Behind it a layer of irregular material full of detachments and voids was detected.

The moisture content test was performed on the roof structure accessible form the north area of the church behind the main altar (Figure 53). Here, the roof structure seemed to be different than from the rest of the church, but it was assumed that for the construction they have used the same materials and for the trusses they have been built with chestnut wood. This non-destructive test was used to measure the moisture content of the timber elements in the superficial part (around 1cm). Moisture content is the ratio between the weight of the water contained in a piece of wood and the weight of the dry wood.

Figure 53 - Roof structure accessible from the north wing area (Betzer et al., 2014).

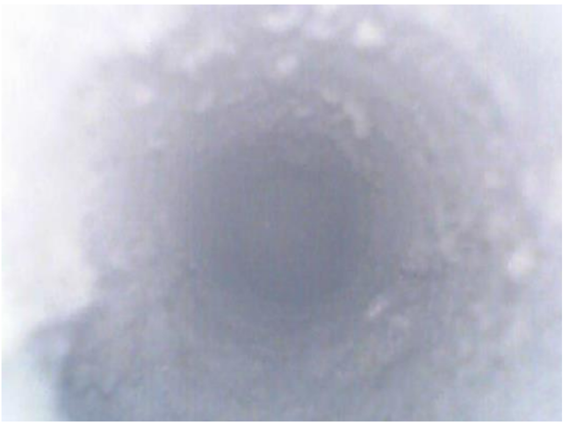
Minor Destructive Testing (MDT) is based on performing of mechanical tests on a small portion of the structural elements of the existing historical structures. It produces some damage that usually does not affect the behaviour of the structure so it does not require any immediate repair or replacement. They are done in situ and are very helpful to obtain more accurate information for the mechanical properties of the historic materials, such as the units (brick or stone) and mortar joints.

Resistograph® test is a MDT that gives an idea of the extent of damage in a timber cross section. It is based in micro-drilling at constant speed, and measures the energy required for maintaining that speed. In this way, the device records changes in the physical quality of wood, giving information about the existence of voids, irregularities or cracks inside the section. In general, the inner parts of the wood are largely free of voids and cracks.

Also, on the wooden roof was performed a Pilodyn test, which aim is to detect the condition of the timber element measuring the depth of penetration of a standard noodle shot in the element by constant energy. This device transforms the elastic potential energy into impact energy through the release of a spring. Therefore, decay behind the surface or reduction of the strength of the timber can be detected by this minor destructive test.

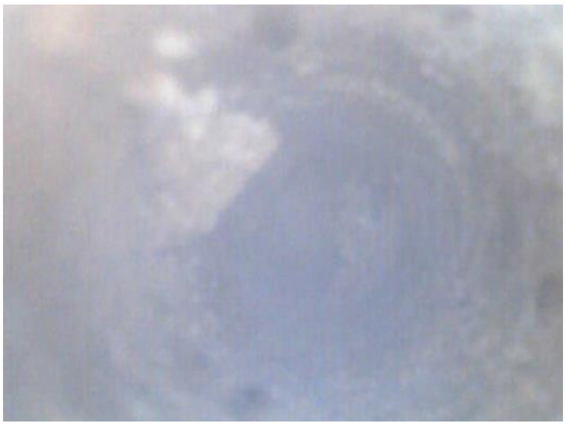
Schmidt hammer test is a minor destructive test used to compare the quality of stones in different parts of the church and to define some of the mechanical properties of the granite stones. The test was performed in many places of the church to stones which are not exposed to strong moisture and weathering effects.

Finally, boroscopic camera test was performed as a minor destructive test on the two side walls of the church (Figure 54 - a and Figure 54 - b) and the covering panel of the vault. This showed homogeneity along the thickness of the walls. The granite walls presented a high amount of moisture content, noticed during the removal of the device from the hole completely wet. With this test, if was confirmed the nonexistence of a three-leaf wall.



a.

b.



c.

d.

Figure 54 – Boroscopic camera test: a. Hole in the north wall-external side; b. Hole in the north wall-internal side; c. Hole in the vault; d. Extracted brick material form the filling of the vault (Betzer et al., 2014).

In the vault, the holes were drilled in the non-structural panel in order to detect its thickness and its material composition. It was reached around 20cm with the boroscopic camera and was extracted a reddish material that was identified as clay material (Figure 54 - a and Figure 54 - b). This material was also observed with the boroscopic test made in the upper part of the vault, where the presence of bricks was clearly defined over a thick mortar layer at a shallow depth. That study was completed by the analysis of partial parts of the building using FEM. The parameters used for the FEM analysis are presented in the following Table 1:

Table 1 - Parameters used for the numerical analysis. (Betzer et al., 2014).

Material properties	Masonry	Ribs	Infill
E [GPa]	2.3	5	0.5
v	0.2	0.2	0.25
ρ [kN/m^3]	20	23	18

According to the damages found in the church, several intervention proposals, recommendations and monitoring were suggested for the roof, the vault, the walls and the soil. A rehabilitation of the old roof and a design of a new roof were proposed as a possible intervention for the roof structure. For better preservation of the heritage structure should be carried out a maintenance plan in order to extend its life time.

In the next chapter, will be discussed the modelling of this particular church by using all the information obtained from the report, available drawings, photo surveys etc. Furthermore, the material properties, damages and some of the interventions proposed will be implemented within the 3D BIM model.

7. CONSTRUCTION OF A 3D MODEL OF A HISTORICAL BUILDING

7.1 BIM concept

Computer Aided Design applications have made major changes over time and their evolution is especially significant for the Architecture, Engineering and Construction (AEC) industry. During the past thirty years, Computer Aided Design (CAD) software has gone from simple two-dimensional drafting programs to integrated (Building Information Modelling) parametric applications. The widespread use of those systems provided new methods for the design and interoperability of the 3D CAD data, contributing also for the modelling of cultural heritage objects and the level of automation for reconstruction processes. Therefore, for a better representation of various information types and for better understanding, visualising and managing a building, having smart connections between all the components, led professionals from the Cultural Heritage field to use BIM systems (Logothetis et al., 2016).

The transition from 2D to 3D CAD is still on going and the total integration of BIM will be in the near future. 2D CAD applications are known as ''electronic drafting boards'' able to provide nothing more than just two-dimensional drawings, without the capacity for implementing 3D models besides basic information related to the type of material. Therefore, the design and documentation are done only in 2D where the drawings are stored in separate files and coordinated manually. The lack of collaboration is the most important part which is missing from that working concept. Additionally, calculation and visualisation tools are not available and because of that the use of different software should be engaged. Certainly, 2D CAD has a lot of advantages in comparison to hand drafting such as fast modifications, intelligent drafting, higher accuracy, which has changed and made it easier the work of the designers (Figure 55). However, the most critical drawback is the lack of automatic drawing coordination (Graphisoft, 2015).

Figure 55 - Hand drafting vs. 2D drawing (Graphisoft, 2015).

The evolution of 3D applications has provided many advantages for architects and engineers compared to 2D and hand drafting. They allow users to create a parametric model of the structure together with the obtained 2D documentation. Drawings can be partially derived from the model (for example some sections or elevations). In the working concept of the 3D CAD, additional content can be created, including some built-in visualization tools and some basic quantity calculation. The main benefits related to 2D CAD are the more accessible identification of design problems and faster management. Even so, it has some drawbacks in comparison with BIM such as the lack of real architectural intelligent elements and automatically updated documentation.

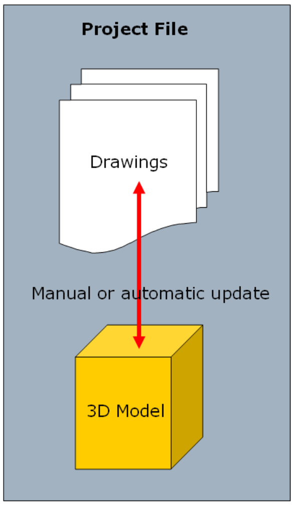


Figure 56 - 3D CAD evolution (Graphisoft, 2015).

Building Information Modelling also known as “Virtual Building” or “Building Simulation” is a platform with a concept of using the 3D building model updated with all the possible information known about the specific structure (Graphisoft, 2015). From the model can be extracted all the required project drawings and building views, as well as additional information can be added from the materials properties into the structural elements (Figure 57). BIM can be considered as an advanced CAD approach, which extends the capability of the traditional design methodology by implementing and defining intelligent relationships between the elements in the designed model. The most significant benefits of this method are the use of a single file concept for the complete building model, which is made by the real architectural elements; management for any changes made into the model; automatic generation and updating of documentation; it has an ample architectural content (library with objects), although most of it is currently defined for new and modern constructions; all information data can be attached to the proper element; and has a lot of additional features such as animation, rendering, schedules, etc. Quantity and energy calculations can be easily done as well as price estimations (Graphisoft, 2015).

Figure 57 - BIM concept (Graphisoft, 2015).

Nowadays, BIM is one of the most used software for modelling new constructions, made by regular elements and standard parameters. What can be used for the management, conservation and maintenance of the existing heritage buildings? Is there any possibility of using BIM process for this purpose? The answer to this question is the goal and purpose of this thesis. By testing a commercial and widely known BIM program, ArchiCAD, which satisfies all the requirements of new and modern buildings, this thesis tries to assess and confirm if it can be used for the Cultural Heritage field, where has to be taken into consideration the complex constructive system made of different structural elements, their complex connections, the materials used, the degradation of the structures and maintenance during their life time.

To effectively test the capabilities of BIM within conservation, reparation and management of cultural heritage, a case study was undertaken with real data, the church of São Vicente, which is important part of the national heritage in Braga, Portugal. All the documentation and information available for the model were extracted from a report done by students of the SAHC master (Betzer et al., 2014). All that was available were a set of 2D drawings, an old photo survey and non-destructive and minor destructive tests from which were obtained some of the mechanical properties of the materials. In Figure 58 is explained the process followed for the completion of a cultural heritage model in a BIM environment.

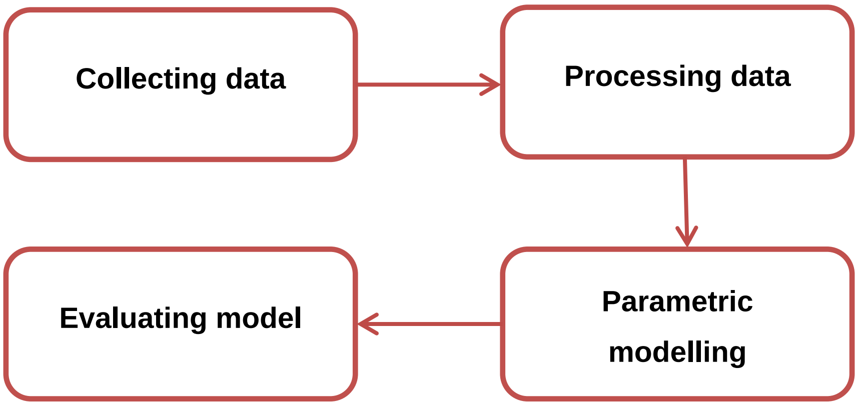


Figure 58 - Stages of completion of a cultural heritage model in a BIM environment (Logothetis et al., 2016).

7.2 Modelling of the church São Vicente

The BIM model of the church of São Vicente was made of real architectural elements that are represented correctly in all the views. These objects are described according to several parameters, some of which are user defined and others, which relate to position in a 3D environment relative to other shape objects (Eastman, 2007). The visualisation of the parametric objects is achieved through viewing 2D and 3D features, plans, sections, elevations and 3D views.

The Industry Foundation Classes (IFC) enables information sharing and interoperability between different platforms and, in this way, it is possible to import the documentation available from AutoCAD to ArchiCAD software, making much easier the creation of the 3D model by having already all the dimensions in 2D and transforming them into 3D (Figure 59, Figure 60 and Figure 61).

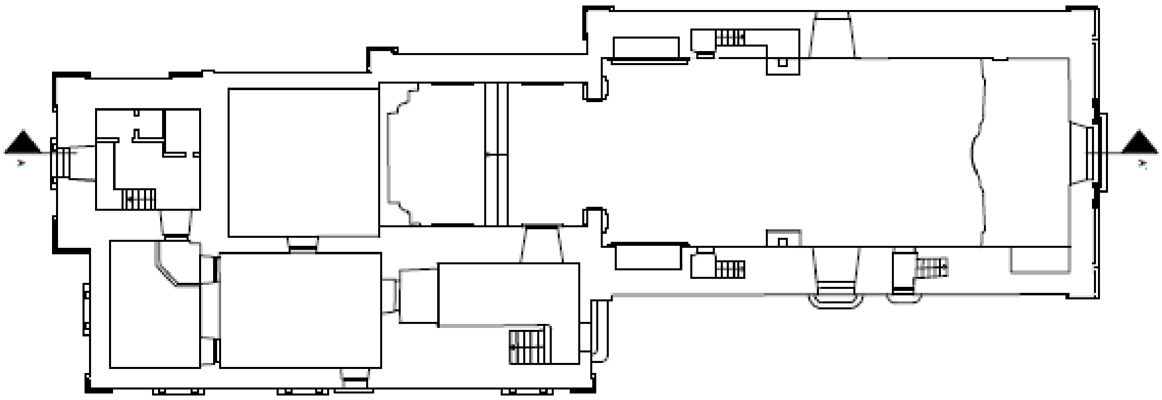


Figure 59 - Floor plan of the church São Vicente (Betzer et al., 2014).

Figure 60 - Section view of the church Sao Vicente (Betzer et al., 2014).

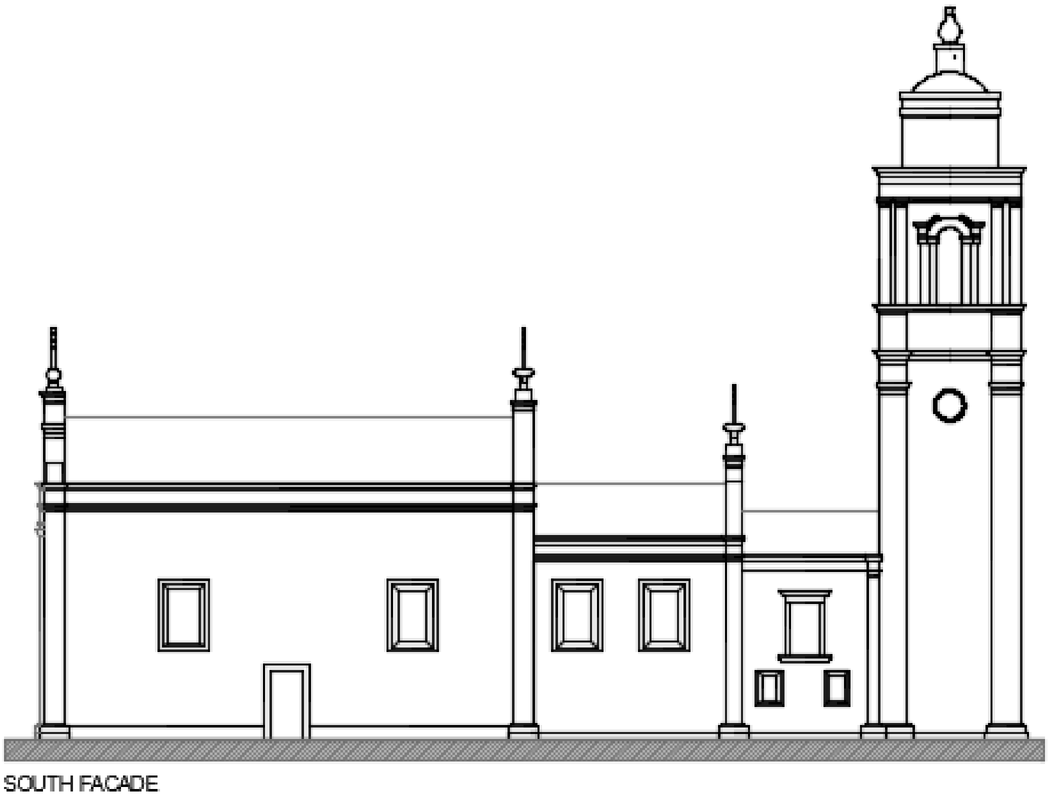


Figure 61 - Elevation of the south facade (Betzer et al., 2014).

The model was built by using the drawings and the photographical survey (Figure 62). Also, two visual inspections were done for a better understanding of the historical building and measuring some of the elements due to the lack of information of the available drawings.

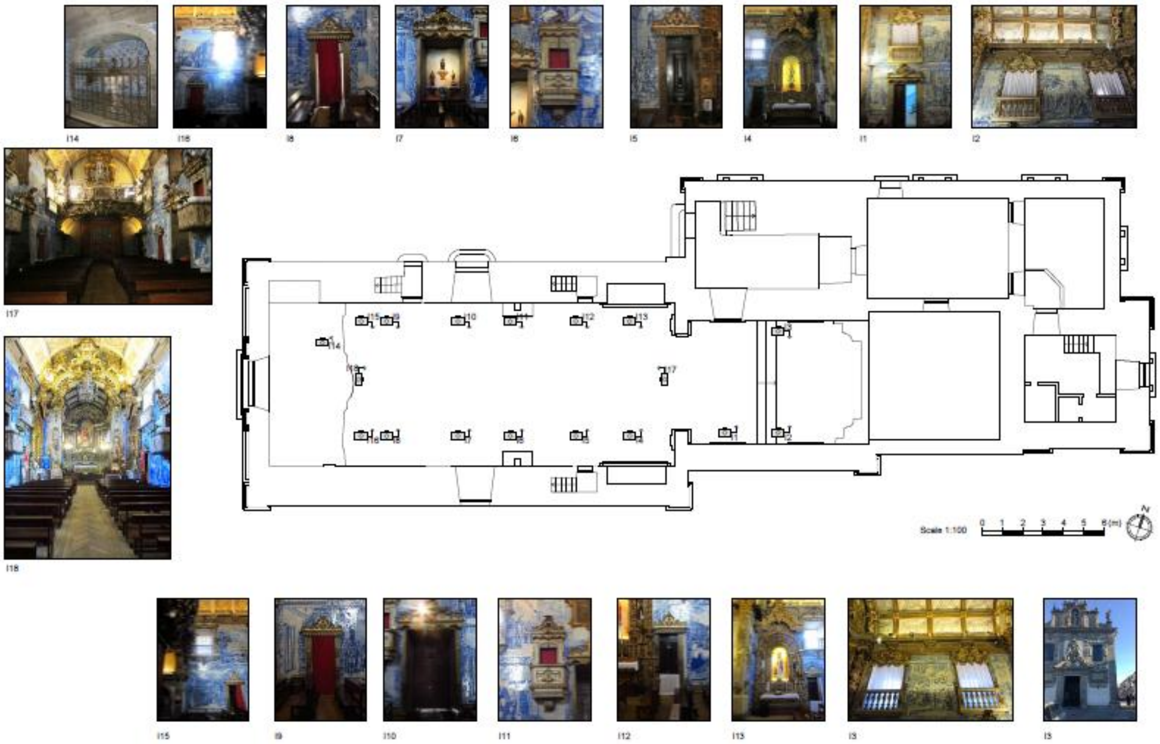


Figure 62 - Photographical survey of the church São Vicente (Betzer et al., 2014).

Therefore, for the 3D BIM model were used the basic structural elements such as walls, slabs, columns and for the modelling of the details was used mostly the Morph tool, which allows for a more flexible and creative design of shapes. Normally, and what was perceived by the use of this software, it is not possible to obtain more accurate visual aspect. For better accuracy, 3D data acquisition can be collected automatically using laser scanners or photogrammetry, but the digital interpretation of point clouds, transformation and fitting into objects has to be performed manually. This process is time-consuming and costly, which reduces the benefits of historical building modelling and refurbishing projects. Also, Geometric Descriptive Language (GDL) for modelling the details or some of the structural elements that are more complex can be used. In this study, those methods were not used due to the time limit and cost. Therefore, all the specific details and elements were created as good as possible with the use of the tools that ArchiCAD as a BIM application provides by default (Figure 63 and Figure 64).

Figure 63 - Detail on the main façade.

Figure 64 - Detail on the upper part of the façade.

The windows and doors were created using the shell tool due to the fact of being specific to historical elements, which are not provided into the standard library of objects in ArchiCAD. Due to the flexibility of the shell and morph tools, it allowed to model any custom geometry in an intuitive graphical way and creating more complex objects characteristic of heritage structures. The important thing is that, even for these objects, the materials properties, their structural function, if they are new or old elements, if they have to be replaced or repaired, etc. can also be implemented. In the following Figure 65 can be seen some of the many different shapes of window, doors and other elements used to model the case study.

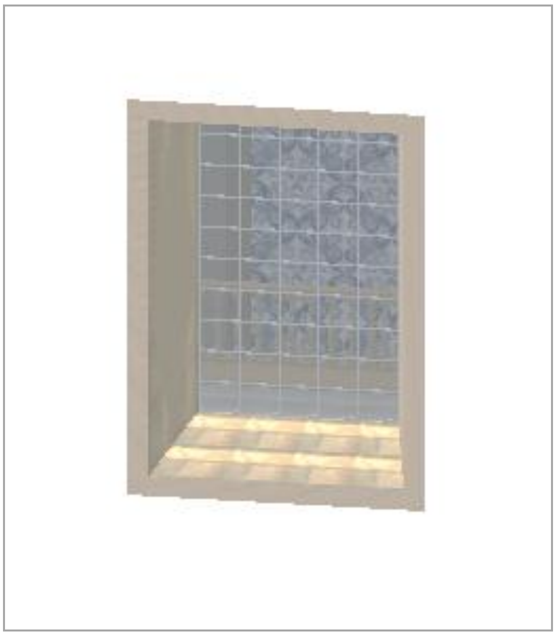


Figure 65 - Window and balcony from the south façade.

The creation of geometric and non-geometric data such as objects specifications and attributes in the BIM model enables different project participants (designers, architects, engineers, conservators, etc.) to visualise both the activities and the progress. The parametric building objects, which represent building components are then used to create an entire building, in this case a historical one. The visualisation of the structural elements and objects is achieved through viewing 2D and 3D features, plans, sections, elevations and 3D views. Figure 66 and Figure 67 present different views of the 3D model of the church São Vicente.

Figure 66 - South facade of the church.

Figure 67 - Eastern view of the church in 3D.

Regarding the modelling part of the church, some simplifications were done due to the parameterisation of the elements (which limits in some cases the shape and location, etc.). The architectural details and decorations, which are non-structural parts of the historical building, were also simplified. However, a sufficient Level of Detail (LOD) was reached by implementing as much as possible information in the model (Figure 68).

Figure 68 - Western main façade of the church of São Vicente, in 3D.

With the help of the parametric 3D BIM model, the management of all the information collected regarding the church is much easier and faster done. Even though the modelling part of such a complex building is complicated and time consuming (some weeks), there are significant advantages in using the BIM model because all of the information needed especially the geometrical will be in one single file and every change, modification or intervention done can be implemented and the model will be updated automatically.

Every engineer working on future projects regarding the church can easily understand the composition, the materials, previous interventions done and what should be done next using the BIM model, without having to do any additional survey. This project management technique with the use of BIM tools has the potential to improve the management and delivery of the digital documentation, concerning any size or complexity of a cultural heritage structure.

The ultimate goal of any architectural and engineer design is to produce the construction documentation more rapidly and easily from which the new buildings can be constructed. This is also important for existing buildings, especially for their conservation and maintenance. BIM can automatically create cut sections, details and schedules in addition to orthographic projections and 3D models. The benefits of this model-based documentation are the coherence between the model and drawings; modifications done on one view are reflected in all drawings; all possible drawings can be derived directly from the model; the complete project lifecycle can be controlled from a single model/file. From the BIM model, it can be easily derived the elevations and section that the designer will need to work with during the project. In the following Figure 69, Figure 70 and Figure 71 some of the drawings extracted from the model will be presented.

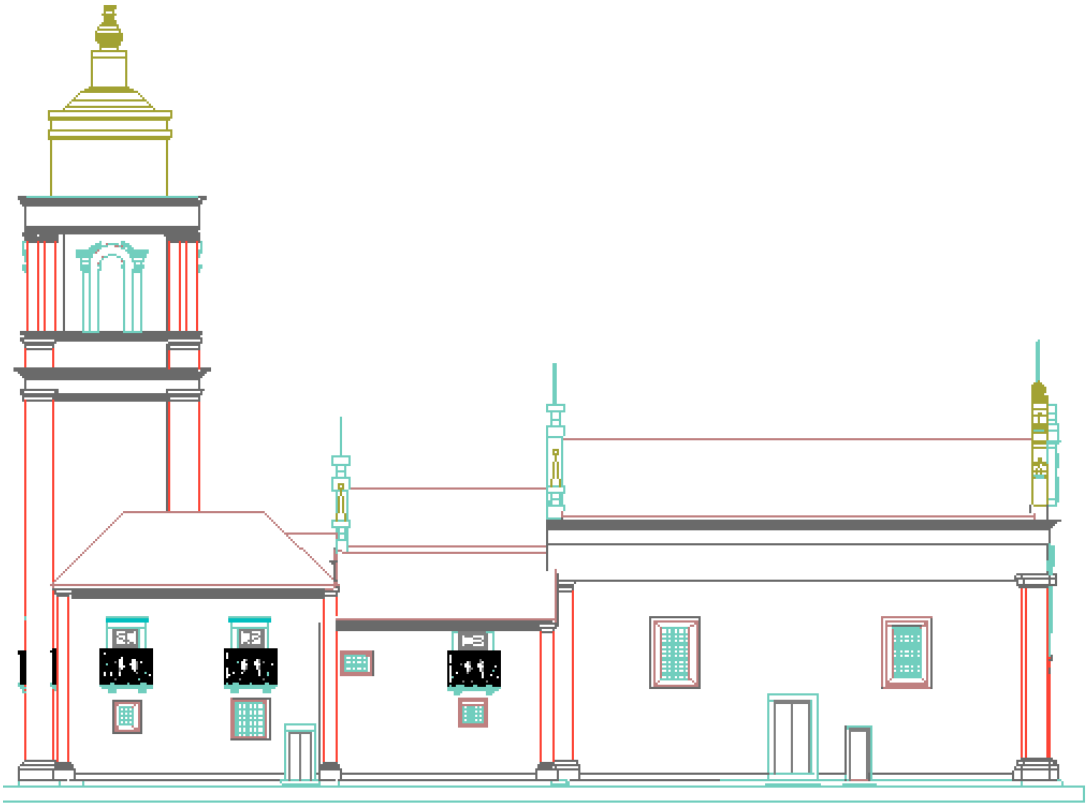


Figure 69 - Elevation of the north façade derived from the 3D BIM model.

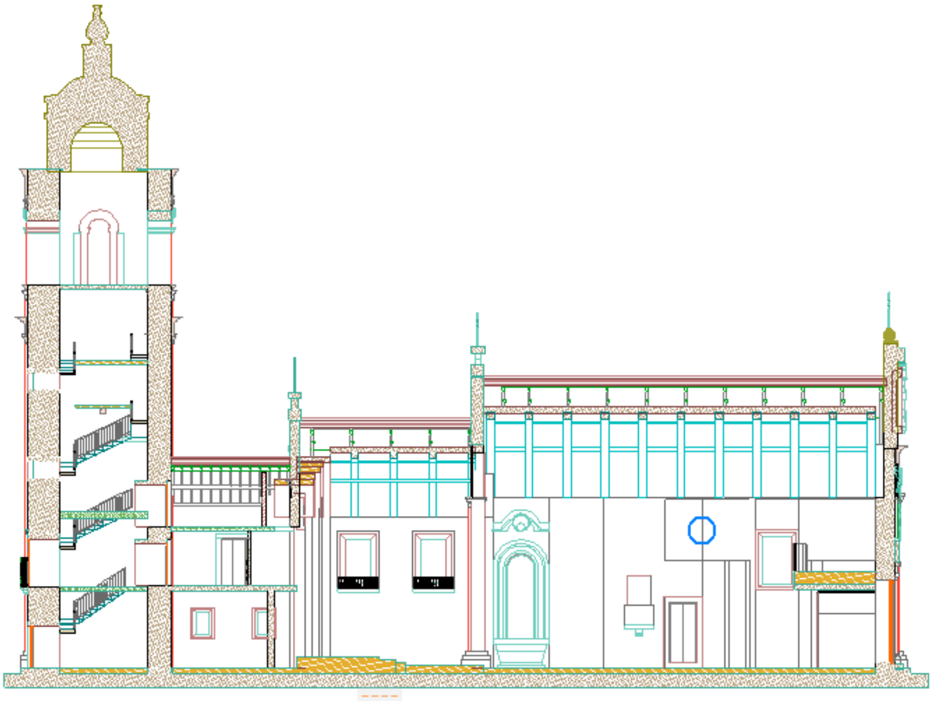


Figure 70 – Section along the centre of the church.

Figure 71 - Sections derived from the 3D BIM model.

The goal of this study of Building Information Modelling of a historical structure is to provide a digital platform, based on the 3D model of the building, which will be used for the planning of subsequent interventions for reparation and conservation, experimental tests, inspections and overall for the maintenance of the building. This has quite a significant number of advantages.

7.3 Communication and collaboration within the BIM model

The communication and collaboration between all the members of the project is essential for the BIM model, to have a more effective control in the design, construction and maintenance of the building. As mentioned previously, there are many formats where the information can be stored. Each professional that is working on the project requires different type of information from the 3D BIM model. So, one solution for some of the problems in the building lifecycle management is the ability to collaborate among all participants.

As a collaboration platform, a BIM server manages, archives building data, and allows applications to export and import files from the database for checking, viewing, modifying and updating the data model. BIM servers allow the exchange of 3D model data between the various applications involved in a BIM project life cycle, including analysis tools, design tools, facility management (FM) tools, document management systems (DMS), etc. (Logothetis et al., 2016).

Members of the buildingSMART organisation have initiated the program Open BIM as a universal approach for the collaborative design, realization and operation of buildings based on open standards and workflows (BuildingSMART, 2007). This application helps AEC software to improve, test and certify their data connections. Open BIM supports an open, transparent workflow, which allows all project members to participate regardless of the software application they are using. It also provides enduring project data for use throughout the building life time, avoiding multiple inputs of the same data and some consequential errors (Graphisoft, 2015).

BIM application can provide renderings, walkthroughs and sequencing of the model for better understanding and visualising the final structure (Logothetis et al., 2016). It can also be used to produce structural models that consist of a part of the parametric objects, without the need to extract the entire model (Eastman et al., 2008).

For the model-based collaboration, the IFC based model exchange was adopted to ensure more accurate calculations and more effective change management. The format establishes an international standard to export and import objects and their properties (Eastman et al., 2008). The BIM model can be transferred to other applications for structural analysis, which has to do an analytical model derived from the physical one (Figure 72). The IFC based structural design workflow covers the preparation of BIM model according to the application the information will be shared with. It can export only the necessary or required elements from the model to others depending on the requested workflow. And it supports also the import of information from other application to the ArchiCAD software (Graphisoft, 2015).

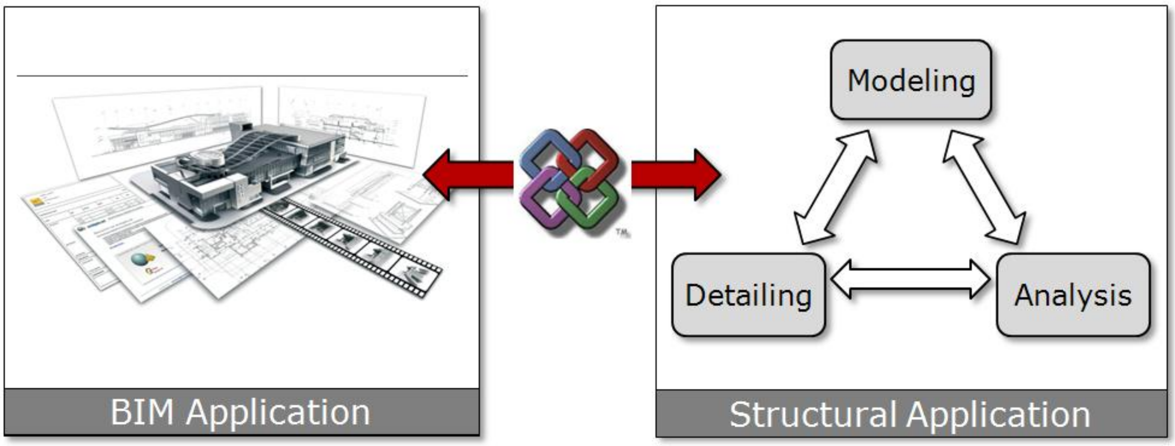


Figure 72 - Exchange of information from BIM to a structural application (Graphisoft, 2015).

The data exchange from the model can be done in three different ways: as a 3D model exchange through the IFC file format or direct model links; 2D drawings such as DWG; and as PDF documentations. Export and import processes are repeated in additional cycles, so tracking changes between architectural or structural model versions is also very easy. A model made by an architect and by an engineer is different in many ways due to the fact that their own disciplines require distinct modelling regulations.

Structural models are simplified versions of the architectural ones because they only contain the load-bearing structural elements such as walls, columns, beams, slabs, roofs and the load-bearing parts of the composite structures. Therefore, for better coordination it is required some model filtering of the BIM model in order to have only building elements needed for the structural analysis. The designer, while creating the model, can define all the elements with their structural function and the materials properties, so for the filtering it will be easier to recognize the structural ones from the architectural elements. This also depends if the program for structural analysis can collect and filter the necessary model data (Graphisoft, 2015).

The model-based exchange can follow one of the two concepts:

- Managing a reference model
- Converting the model to native formats

Using the reference model concept (Figure 73), the architectural and structural model files remain intact, because each office is responsible for their own model. They are taking into account the other model suggestions without modifying anything. In this way, each discipline’s own file is independent of the one received as a reference.

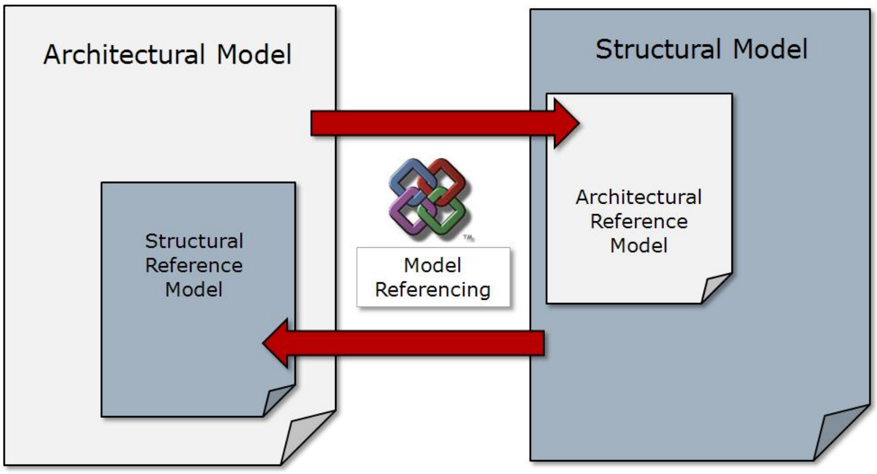


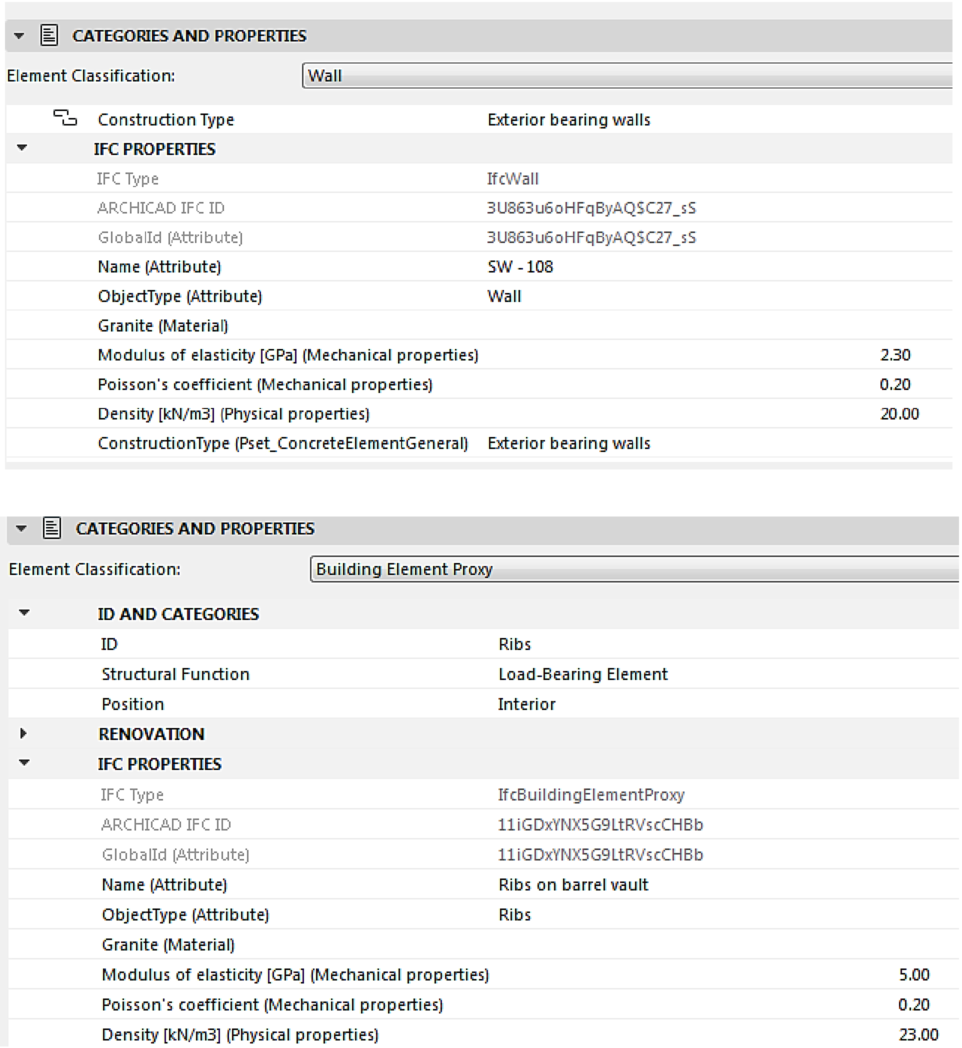
Figure 73 - Reference model concept (Graphisoft, 2015).

The other approach for the model-based exchange is to convert the other participants' model elements into the native format of everyone's own application. The converted model is transformed according to the specifications of the recipient, so the original version of the model is not preserved. In general, this approach is most typical of data exchange between architectural and analysis programs (Graphisoft, 2015).

7.4 Implementation of material properties in the IFC files

ArchiCAD, as every other BIM software, has a wide range of different intelligent building materials mostly used for the construction of new and modern buildings. Due to the lack of materials that were used for the construction of historical structures, these had to be added manually. Additionally, for a proper assessment of the structural behaviour and for the safety assessment of the building, the mechanical and other important physical properties have to be defined and to be available, to avoid these properties to have to be constantly estimated/tested or only available in scattered reports.

BIM software has only information about the physical and thermodynamic properties of the materials used for building, mostly related to the fact that new buildings must have thermal calculations properly done. Therefore, the implementation of the other properties can be done through the IFC file by adding new IFC properties to each structural element. Mechanical properties such as compressive and tensile strength, elastic modulus, Poisson's ratio, and physical properties such as density, porosity, are some of the properties necessary to implement in the model IFC properties. Figure 74 shows screenshots from these properties.



CATEGORIES AND PROPERTIES		
Element Classification:	Wall	
Construction Type	Exterior bearing walls	
IFC PROPERTIES		
IFC Type	IfcWall	
ARCHICAD IFC ID	3U863u6oHFqByAQSC27_sS	
GlobalId (Attribute)	3U863u6oHFqByAQSC27_sS	
Name (Attribute)	SW - 108	
ObjectType (Attribute)	Wall	
Granite (Material)		
Modulus of elasticity [GPa] (Mechanical properties)		2.30
Poisson's coefficient (Mechanical properties)		0.20
Density [kN/m3] (Physical properties)		20.00
ConstructionType (Pset_ConcreteElementGeneral)	Exterior bearing walls	

CATEGORIES AND PROPERTIES		
Element Classification:	Building Element Proxy	
ID AND CATEGORIES		
ID	Ribs	
Structural Function	Load-Bearing Element	
Position	Interior	
RENOVATION		
IFC PROPERTIES		
IFC Type	IfcBuildingElementProxy	
ARCHICAD IFC ID	11iGDxYNX5G9LtRVscCHBb	
GlobalId (Attribute)	11iGDxYNX5G9LtRVscCHBb	
Name (Attribute)	Ribs on barrel vault	
ObjectType (Attribute)	Ribs	
Granite (Material)		
Modulus of elasticity [GPa] (Mechanical properties)		5.00
Poisson's coefficient (Mechanical properties)		0.20
Density [kN/m3] (Physical properties)		23.00

Figure 74 - Implementation of mechanical properties in the IFC.

Taking into consideration the importance of those properties for the management, conservation and maintenance of the cultural heritage, hopefully in the near future some improvements of the IFC are going to be made and more properties are going to be implemented to the materials in the existing library of intelligent building materials in ArchiCAD.

7.5 Implementation of damages

The damage identification that has been done in the report for the church São Vicente can be implemented in the model only with the IFC properties. Unfortunately it is not yet possible to draw cracks on the model or to show some of the decays. However, all the information can be placed as a comment to each element where it can be described what kind of damage it is, where exactly is its position on the structural element, the depth and thickness of the crack, if it is old or new, if it is structural or not etc (Figure 75, Figure 76 and Figure 77).

CATEGORIES AND PROPERTIES		
Element Classification:	Roof	
ID AND CATEGORIES		
ID	SHELL - 003	
Structural Function	Load-Bearing Element	
Position	Interior	
RENOVATION		
GENERAL RATINGS		
MAIN CONSTRUCTION		
IFC PROPERTIES		
IFC Type	IfcSlab	
ARCHICAD IFC ID	130F2JTGr5o9wA_G4DRAyS	
GlobalId (Attribute)	130F2JTGr5o9wA_G4DRAyS	
Name (Attribute)	SHELL - 003	
ObjectType (Attribute)	Barrel vault	
PredefinedType (Attribute)	ROOF	
Cracks and damage related to moisture (Damage Identification)		
Granite (Material)		
Modulus of elasticity [GPa] (Mechanical proprties)		2.30
Poisson's coefficient (Mechanical proprties)		0.20
Density [kN/m3] (Physiscal proprties)		20.00

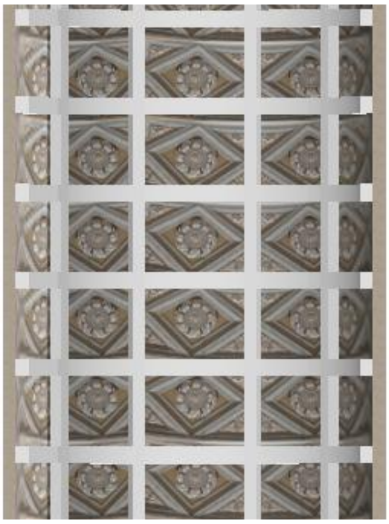
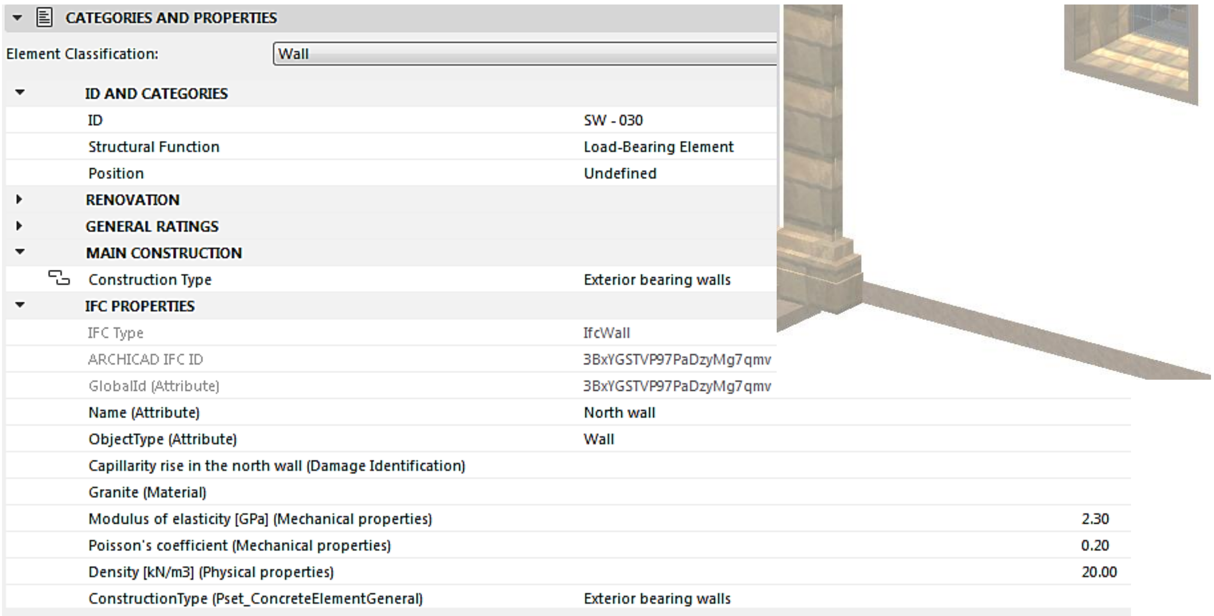


Figure 75 - Implementation of damages on the vault as a comment in the IFC properties.

CATEGORIES AND PROPERTIES		
Element Classification:	Wall	
ID AND CATEGORIES		
ID	SW - 132	
Structural Function	Load-Bearing Element	
Position	Undefined	
RENOVATION		
GENERAL RATINGS		
MAIN CONSTRUCTION		
Construction Type	Exterior bearing walls	
IFC PROPERTIES		
IFC Type	IfcWall	
ARCHICAD IFC ID	0Pyz6NkKzDdP1WCpc2FcXu	
GlobalId (Attribute)	0Pyz6NkKzDdP1WCpc2FcXu	
Name (Attribute)	SW - 132	
ObjectType (Attribute)	Wall	
Craquele cracks on the plaster of the bell tower (Damage Identification)		
Granite (Material)		
Modulus of elasticity [GPa] (Mechanical properties)		
Poisson's coefficient (Mechanical properties)		0.20
Density [kN/m3] (Physical properties)		20.00
ConstructionType (Pset_ConcreteElementGeneral)	Exterior bearing walls	

Figure 76 - Implementation of damages on the bell tower as a comment in the IFC properties.



CATEGORIES AND PROPERTIES

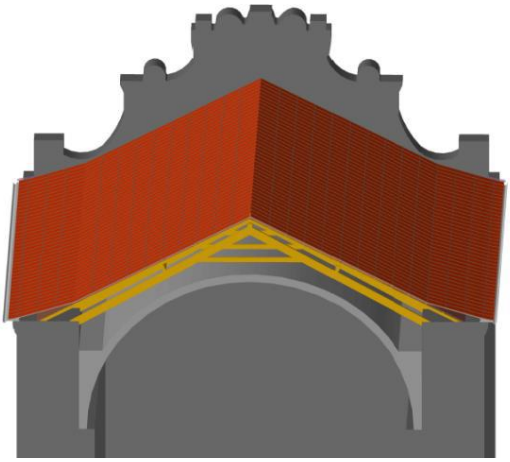
Element Classification:	Wall	
ID AND CATEGORIES		
ID	SW - 030	
Structural Function	Load-Bearing Element	
Position	Undefined	
RENOVATION		
GENERAL RATINGS		
MAIN CONSTRUCTION		
Construction Type	Exterior bearing walls	
IFC PROPERTIES		
IFC Type	IfcWall	
ARCHICAD IFC ID	3BxYGSTVP97PaDzyMg7qmv	
GlobalId (Attribute)	3BxYGSTVP97PaDzyMg7qmv	
Name (Attribute)	North wall	
ObjectType (Attribute)	Wall	
Capillarity rise in the north wall (Damage Identification)		
Granite (Material)		
Modulus of elasticity [GPa] (Mechanical properties)		2.30
Poisson's coefficient (Mechanical properties)		0.20
Density [kN/m3] (Physical properties)		20.00
ConstructionType (Pset_ConcreteElementGeneral)	Exterior bearing walls	

Figure 77 - Implementation of damages on north wall as a comment in the IFC properties.

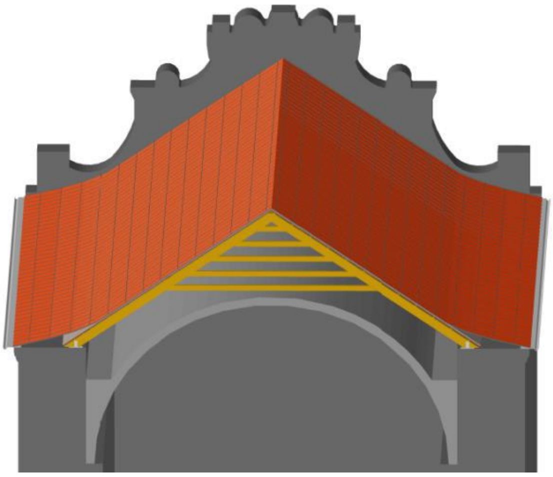
This can be very helpful for the further interventions that are going to be done on the same structure. Furthermore, with the repair of any crack or other damage, this information can be easily updated into the model. Also with every new visual inspection done to the historical building, new damages that will be noticed are going to be implemented in the IFC properties to the particular structural element. In future works, it should be taken into account the improvement of this matter, in order to be possible to visualize the existing alterations in the historical structure.

7.6 Implementation of some interventions

In the report done for the church of São Vicente, an intervention proposal has been given. Using BIM, any intervention done on the structure can be easily implemented and changed in the 3D model. Two intervention alternatives were proposed (Figure 78), both of which involved the rehabilitation of the old roof. These interventions were design with minimal intrusion by trying to preserve the traditional and original materials, keeping the authenticity of the building intact. The second proposal was the design of a new roof where some minor alterations to the geometry were proposed in order to facilitate ease of access for maintenance.



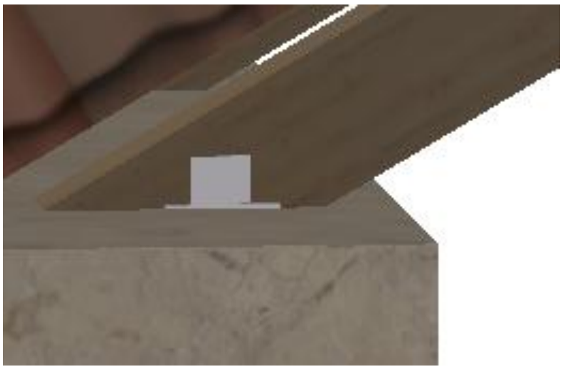
a.



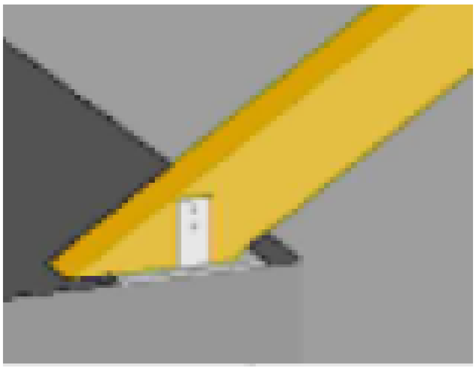
b.

Figure 78 - a. Rehabilitation proposal; b. New roof proposal (Betzer et al., 2014).

Therefore, the roof in the model of the church Sao Vicente has to be changed. Therefore, in the properties of the roof, it is possible to be commented that the current roof structure is for repair or rehabilitation. Additionally, with the modelling of the new, or repaired, roof, which is shown in Figure **79**, in its IFC properties can be implemented many characteristics such as the date of when the intervention was done, the company responsible for the intervention, the materials used for the new roof, etc. This important information is totally absent from some of the existing Portuguese Heritage buildings.



a.



b.

Figure 79 – a. Intervention on the roof derived from the 3D BIM model
b. Intervention proposed (Betzer et al., 2014).

Figure 80 – New roof modelled with all information implemented in IFC properties.

This is important for the management of the cultural heritage, because every intervention done on the structure can be very easily changed in the model. Therefore, the owner and the professionals responsible for the management and maintenance of the historical building will have all the information implemented in the model and digitalized. Even after many years, if other company will be in charge for the reparation and restoration of the church they will not have the necessity to investigate what was done and do more investigation about the building, due to the fact that all needed historic data will be incorporated inside one single BIM model/file.

7.7 Maintenance

Interventions done on heritage buildings are very complex, since every project is unique due to the convolution of the different historical layers and different professionals involved in the case project. The complexity of interventions on historic sites and buildings inquires for a specific approach that takes into consideration both the complexity of existing historic structures as well as the specificity of historic building materials and construction techniques (Rashid et al., 2011).

The conservation of historic buildings is an established method to preserve a heritage structure through restoration and maintenance works. Maintenance has been identified as a key intervention in protecting historic structures by prolonging buildings lifespan. Planned preventive conservation is a management approach that achieves the preservation of cultural significance by continuous improvements of the state of conservation, rather than by ‘after damage’ restoration. This approach can guarantee a better preservation of cultural significance, if applied strategically, and it aims at a long-term cost savings.

In building conservation, maintenance is defined as the routine work, which carried out regularly on a planned basis that is necessary to protect the fabric of the built heritage excluding the repairing process (Mohd-Isa et al., 2011). All international guidelines and charters emphasise the importance of regular maintenance based on the principle of minimal intervention for maintenance works. The Venice Charter 1969 states, "It is essential to the conservation of monuments that they be maintained on the regular basis".

Preventive maintenance is a systematic and routine maintenance process designed to extend the useful life of building materials, structural components, and systems. Through regular servicing and minor repairs, this maintenance extends the building's important lifetime by interrupting the natural process of deterioration. Some examples of preventive maintenance include routine repointing of masonry walls, routine cleaning of roof gutters, and the seasonal pruning of vegetation around structures (Rushlow and Kermath, 1994).

Taking care of the monuments and historical constructions, by guarantying their authenticity and tangible expression, requires systematic and regular maintenance of the cultural heritage. For carrying out the maintenance plan it is expected to be done very regular inspections of the structural conditions of the building as well as the interior conditions and valuable artefacts (Monumentenwacht, 2017).

Nowadays, there are many examples of maintenance systems and one of them is the Monument Watch from Belgium. With the motivation "Prevention is better than cure" this system operates for the conservation and maintenance of the built cultural heritage. They carry our two types of monitoring inspection: architectural and interior inspections (Monumentenwacht, 2017).

Another initiative that seeks similar objectives is the HeritageCare project, which main goal is to unfold an integrated and sustainable methodology for the preventive conservation and maintenance of historic and cultural built heritage, based on a joint system of services and products provided by a self-sustainable non-profit entity. This pilot project is being carried out in Portugal, Spain, and France (HeritageCare, 2017). In Figure 81, the management levels are presented, which are carried out within this project.

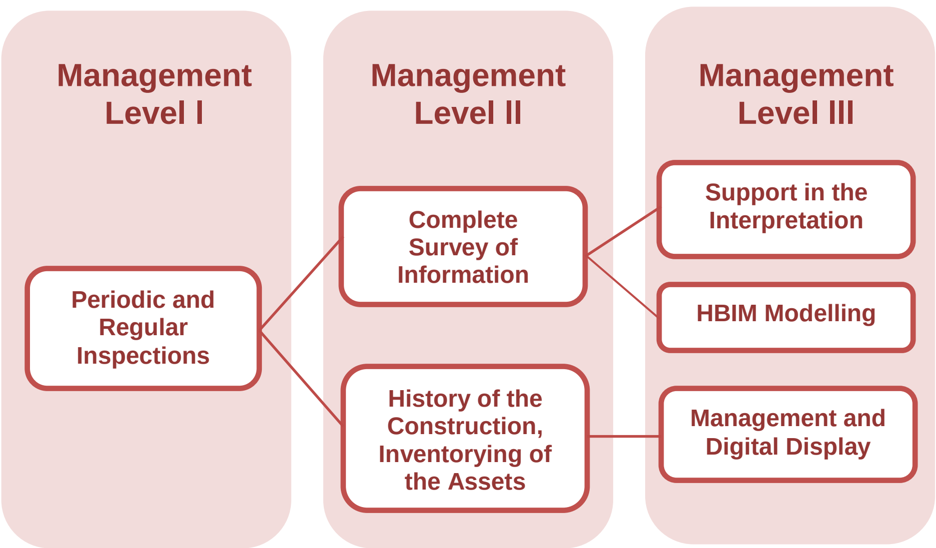


Figure 81 - HeritageCare Methodology (HeritageCare, 2017).

The management approach starts with a clear understanding of the cultural significance of a building. This definition should be constantly reviewed and updated. The state of conservation of a building is assessed by performing a condition survey. Annual inspections will review and update the condition survey and will refine the annual program of actions and interventions (Rashid et al., 2011).

ICOMOS (1964) stated that maintenance is defined as the continuous caring performed to prevent the structure, fabric and the positioning of the building, of which these differ from the concept of repair works which include the restoration works or reconstruction works and these require comprehensive planning.

A management and maintenance plan is a document in which is set out what maintenance and management you need to do, when you will do it, and who will do it. It also tells how much it will cost and how/who to monitor the work. A plan can help taking care of heritage, thinking about resources, and ensuring the same problems don’t arise again in the future.

Maintenance is the routine of periodically work done which is needed to prevent further decays and damages. Every maintenance plan should have the following activities (Van Roy et al., 2015):

- Periodic cleaning of the roof;
- Clearing gutters and keeping drains clear;
- Cleaning of the plumbing pipes;
- Maintaining lighting;
- Maintaining facilities for visitors and other services;
- Keeping paths, fences and means of access in good condition;
- Painting woodwork and replacing slipped roof tiles;
- Painting walls;
- Cleaning of the stones;
- Use of anti-corrosive coating in order to avoid corrosion in windows;
- Keeping working objects in good operational condition;
- Keeping digital outputs working as intended;
- Dealing with litter, waste collection and disposal;
- Housekeeping and routine cleaning;
- Regular inspections of equipment, structures and services; and
- Taking care for trees and other vegetation.

All of these activities should be done in a period of six months or at least once a year. Many of the problems that are facing most of the heritage monuments are the result of long-term neglect or lack of maintenance. Therefore, the management of the historical structure should include a maintenance plan to keep the structure in good conditions and to avoid future interventions.

Good management and maintenance are crucial to the long-term care of heritage sites, collections and assets which means having the proper skills and procedures to ensure that they are looked after. Poor management and maintenance puts heritage at risk and can lead to higher costs in the future. It is in the nature of any material to degrade with time; hence, even if the structure is in perfect condition at any point of time, maintenance is always of utmost importance to upkeep the performance of the structure (Van Roy et al., 2015).

In theory, a well-maintained building can exist and function indefinitely. In practice, however, buildings do deteriorate over time. Not all building component failures can be anticipated, much less prevented. Buildings experience random failures and deficiencies that no amount of planning or careful monitoring can prevent if maintenance is not carried out (Rushlow and Kermath, 1994).

Using BIM process, it can be easily extracted all the information needed for the maintenance plan without the need of going to the building and doing an inspection. The BIM method is not just a model, but a comprehensive database which can automatically generate various reports such as quantity take-offs, door-window schedules, cost estimations, etc. The elements of the model can be individually listed or also by selecting some of their attribute a group of different elements can be put in the same category automatically done by the software.

For the maintenance of the walls, in the case of repointing, restore plasters, replacing glazed tiles, etc., information about the area, volume, thickness, height, perimeter, length can be obtained from the quantity calculations. Additionally, different properties can be inserted in the table such as the material type, physical and mechanical properties, the texture applied to the surface of the walls (for example: painted or covered with tiles), if the element is old or replaced, etc. Everything is digitalized so there is no need of doing any measurement and calculations are easy to perform. After some interventions, or repairs, the model can be updated with the new information. In the following Table 2, Table 3 and Table 4 part of the possible information that can be obtained from the model is presented.

Table 2 – Wall Schedule.

Full Element ID	2D Plan Preview	Wall Type	Height [m]	Thickness [m]	Area [m2]	Net Volume [m3]	Perimeter of the Wall [m]	Construction Type
SW - 008		Stone - Structural	8.3	0.69	4.66	30.59	14.9	Exterior bearing walls
SW - 015		Stone - Structural	8.7	1	5.5	42.38	13.3	Exterior bearing walls
SW - 016		Stone - Structural	4.2	0.811	3.99	8.83	11.47	Exterior bearing walls
SW - 019		Stone - Structural	8.4	0.819	9.45	57.59	25.2	Exterior bearing walls
SW - 020		Stone - Structural	6.8	1	9.68	56.84	21.37	Exterior bearing walls
SW - 024		Stone - Structural	7.65	1.5	0.55	2.08	3.74	Exterior bearing walls
SW - 025		Stone - Structural	7.7	1.282	11.4	67.59	20.35	Exterior bearing walls

Table 3 - Window Schedule.

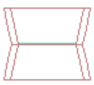
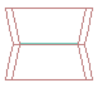
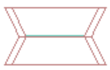
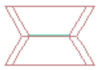
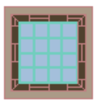
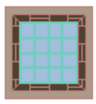
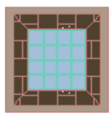
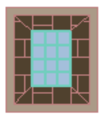
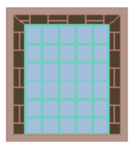
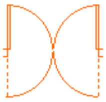
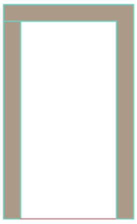
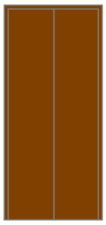
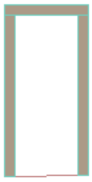
Full Element ID	WD - 009	WD - 010	WD - 015	WD - 016	WD - 018
Quantity	1	1	1	1	1
W x H Size	1.194x1.256	1.194x1.256	1.396x1.457	1.221x1.430	1.654x1.840
Orientation	R	R	L	R	R
Sill height	1.5	1.5	1.8	2.025	1.739
Head height	2.756	2.756	3.257	3.455	3.579
2D Symbol					
View from Side Opposite to Opening Side					

Table 4 - Door Schedule.

Full Element ID	DOO - 007	DOO - 012	DOO - 021	DOO - 022	DOO - 048
Quantity	1	1	1	1	1
W x H Size	1.381x2.385	0.986x2.124	1.996x3.361	1.364x3.044	1.142x2.361
Orientation	L	R	R	R	R
Sill height	0	4.2	0	0	0
Head height	2.385	6.324	3.361	3.044	2.361
2D Symbol					
View from Side Opposite to Opening Side					

These calculations can be done for each parametric element that is included in the BIM model. In this way, the maintenance for the historical structures will be more easily and faster done, without losing time for measurements and calculations.

8. CONCLUSIONS

Nowadays, the use of Building Information Modelling (BIM) has become very relevant in different fields of application. BIM is not just a program but a process that supports the design, construction, information sharing and management of buildings. Although it was created for the design and construction of new and modern buildings, it can also be used as an approach to help in the maintenance of historical buildings. The benefits of BIM are important and useful for the comprehension of Cultural Heritage from a management point of view. Despite this, there are still many drawbacks for the use of BIM with Heritage buildings.

The process of HBIM, which involves collection and processing of laser/image survey data, identification of historic details from historical documents, construction of parametric historic elements, correlation and mapping of parametric objects onto scan data and obtaining the documentation of 2D drawings, was described in order to better comprehend the challenges and difficulties for the utilisation of BIM in the Cultural Heritage (Murphy et al., 2013). In addition, the HBIM automatically intents to produce full engineering drawings from historic structures and environments, which will include 3D documentation, orthographic projections, elevations, sections, details and schedules, etc.

The aim of this master thesis is to test, with real data from a real Cultural Heritage case study, the BIM process and highlight the advantages, challenges and difficulties. For that purpose, a parametric model of the church of São Vicente was created from basic structural elements provided by the program ArchiCAD. All the information regarding the structure was obtained from a previous on-site report, which included material and damage characterization of the church and proposed some interventions. Due to the lack of information difficult to be obtained, some assumptions and simplifications were assumed during the modelling. There are a number of general limitations to BIM, as well as several limitations specific to this case study. As in the research from Foxe (2010), it is pointed out that *“the certainty and precision of the model are only as powerful as the knowledge and accuracy that went into creating it.”*

One of the challenges that remain is the development of a set of parametric building objects to accurately represent the complex structural components, including their behaviour, their connections and the relationships between them. For that purpose, GDL can be used for the modelling of the complex elements and details typically found in historical buildings. Laser scanning or photogrammetry can be used for collecting the 3D data automatically, but the digital interpretation of the point clouds has to be done manually. The main challenge involved in the use of laser scanning is to capture not only the precise geometry with all details but also to be able to generate semantically meaningful structural components as parametric with the ease of implementation of all the data available.

The accuracy of the 3D BIM model depends on some requirements such as the level of detail (LOD). However, the goal was to achieve the creation of full 3D model of the church of São Vicente by adding intelligent information for the building materials properties, existing damages and deteriorations and possible interventions that should be carry out. Therefore, it was not possible, or needed, to obtain high accurate visualisation.

Additionally, the creation of a BIM model simultaneously allows and demands the user to understand the elements, comprising the totality of the actual structure with all the connections. The model can be viewed in any of a multitude of projections and sections, and subjected to 3D manipulations to compare it against the building itself and inspect it for accuracy and completeness.

BIM models can provide material quantity take-off which is very helpful regarding the maintenance and can be used for further structural analysis with some model filtering done to better recognize the structural elements from the architectural ones.

In general, BIM allows collecting and classifying heterogeneous information. It is certain that a well-constructed and supported BIM model can have an extended, and an expanded utility, to monitor the behaviour, performance and deterioration of the heritage building, using all the meaningful information that will increase the productivity, profitability and accuracy of a project done in the Cultural Heritage field and also help for its long-term preservation.

BIM is an application of the future and very soon will be used not only for modern buildings but also for our Cultural Heritage. However, there is still a lot to be done regarding this topic and hopefully the technologic barrier will be overcome very soon. The goal was to try until what level could be obtained the 3D BIM model and what information can be implemented for the further help of management of historical buildings, mostly putting an accent to the challenges during the whole modelling process. Consequently, it is very important to keep updated because the BIM process is in progress constantly, always with some new upgrades and it is directed towards the heritage world.

Further research and improvement has to be done regarding the IFC data model in order to implement into the BIM model additional fields related to all materials properties, methods of construction (double and triple leaf walls, dry joint, thick joints, masonry with lime mortar, etc.), connections and damage identification, as these types of information are significantly relevant for the management of heritage buildings, as well as analyses and other processes.

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