Protocol to manage heritage-building interventions using Heritage Building Information Modelling (HBIM)

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ABSTRACT

Heritage architectural projects involve collaborative work between different stakeholders, e.g. architects, engineers, archaeologists, historians, restorers, managers, etc. Traditionally, each discipline works independently, generating dispersed data. The workflow in historic architecture projects presents problems related to the lack of clarity of processes, dispersion of information, and the use of outdated tools. Different heritage organisations have showed interest in innovative methods to resolve those problems. Building Information Modelling (BIM) has emerged as a suitable computerised system to improve the management of heritage projects. BIM application to historic buildings, named Heritage Building Information Modelling (HBIM), has shown benefits in managing heritage projects. The HBIM literature highlights the need for further research in terms of the overall processes of heritage projects, its practical implementation, the need of simplifying the laborious modelling task, and need for better standards of cultural documentation.

This investigation aims to develop a protocol for heritage project processes using HBIM and an online work platform prototype where interdisciplinary stakeholders can unify and synchronise heritage information. Design Science Research (DSR) is adopted to develop this protocol. Research techniques used include documentary analysis, case studies, semi-structured interviews, participative workshop, and focus groups. An analysis of HBIM processes and a study of heritage stakeholders' requirements were performed through documentary analysis and semi structured interviews with stakeholders involved with relevant monuments. HBIM is proposed as the virtual model which will hold heritage data and will articulate processes. As a result, a simple and visual HBIM protocol, BIMlegacy, was developed. It is divided in eight steps and it contemplates all the stakeholders involved. BIMlegacy was applied in the Fixby Hall case study and its results were evaluated in a workshop with interdisciplinary stakeholders. An online work platform prototype, also named BIMlegacy, was developed, where interdisciplinary stakeholders can unify and synchronise heritage information. This innovative in-cloud system connects the intrinsic HBIM software database with heritage documentary databases using a Revit Autodesk Plug-in, a web Application Program Interface, a Structured Query Language server, and a web portal. BIMlegacy is an online platform to facilitate working but also a cultural diffusion web where general visitors can access to the information of the monuments. The BIMlegacy protocol and platform were implemented in two case studies Fixby Hall in Huddersfield (United Kingdom) and San Juan del Hospital in Valencia (Spain). BIMlegacy and the results of San Juan project were revealed in a workshop and in a focus group with external professionals for its evaluation.

This research contributes within the theoretical knowledge highlighting modelling issues that were unknown before, benefits of using HBIM (a.e. the use of online platforms, filtering the information in HBIM database systems, the integration of cultural divulgation with HBIM) and needs in terms of implementing HBIM in practice such as the importance to have a simple and intuitive protocol to be useful and that the non-designer stakeholders require specific HBIM training. The practical contributions are the creation of the BIMlegacy protocol with the list of stakeholders and processes, the design of the BIMlegacy platform with the synchronisation of information in real time allowing the non-technical stakeholders to actively participate in HBIM models, the use of HBIM as management system, and the benefit for society and local communities since the rigorous information uploaded by professionals will be accessible to the public.

RESUMEN

Los proyectos de arquitectura patrimonial conllevan trabajo colaborativo entre diferentes agentes tales como arquitectos, ingenieros, arqueólogos, historiadores, restauradores, propietarios, etc. Tradicionalmente cada disciplina ha trabajado de manera independiente generando información dispersa. El flujo de trabajo en los proyectos patrimoniales presenta problemas relacionados con la desorganización de procesos, la dispersión de información y el uso de herramientas obsoletas. Diferentes organizaciones abogan por usar métodos innovadores para tratar de resolver estos problemas y hacer del patrimonio cultural un motor de desarrollo socioeconómico. BIM (Building Information Modelling) se ha postulado como una metodología adecuada para mejorar la gestión del patrimonio arquitectónico. La aplicación de BIM a construcciones históricas, denominada HBIM (Heritage Building Information Modelling), ha probado tener múltiples ventajas para gestionar proyectos patrimoniales. Sin embargo, la literatura científica pone de manifiesto la necesidad de seguir investigando en los procesos de los proyectos patrimoniales, la implementación práctica de HBIM, la simplificación de la laboriosa tarea de modelado HBIM y la documentación de los proyectos HBIM.

La finalidad de esta investigación es el desarrollo de un protocolo que ordene la gestión de proyectos patrimoniales usando HBIM y el diseño de una plataforma web que sincronice la información patrimonial. DSR (Design Science Research) es el método de investigación usado para desarrollar dicho protocolo que ayude a mejorar el flujo de trabajo en los proyectos patrimoniales. Las técnicas de investigación usadas han sido el análisis documental, casos de estudio, entrevistas semiestructuradas y grupos focales. Se analizaron los procesos HBIM y se estudiaron los requerimientos de los agentes patrimoniales. HBIM se propuso como el modelo virtual que acoge la información patrimonial y que articula los procesos. Como resultado, se desarrolló el protocolo BIMlegacy, dividido en ocho pasos y contemplando a todos los agentes que participan en proyectos patrimoniales. Dicho protocolo se aplicó en el caso de estudio real de Fixby Hall, edificio histórico en Huddersfield (Reino Unido), y sus resultados fueron expuestos en un workshop interdisciplinar en Huddersfield para validar y mejorar el protocolo BIMlegacy. Basado en este protocolo, se desarrolló la plataforma BIMlegacy como herramienta para poder llevar a cabo este flujo de trabajo donde agentes interdisciplinares pueden unificar y sincronizar la información patrimonial. Este innovador sistema en la nube conecta la base de datos intrínseca de los programas HBIM con bases de datos patrimoniales usando un plug in para Revit de Autodesk, una web API, un servidor SQL y un portal web. La plataforma BIMlegacy se diseñó como una web de trabajo, pero también como una web de difusión cultural donde el público generalista puede acceder a cierta información de los monumentos. El protocolo y la plataforma BIMlegacy fueron usados para gestionar el proyecto de Registro de San Juan del Hospital de Valencia (España). El protocolo fue explicado en un workshop en

Huddersfield, Reino Unido para su evaluación con profesionales interdisciplinares. Posteriormente, el protocolo, la plataforma y los resultados del proyecto de San Juan del Hospital fueron expuestos en un grupo focal en Valencia con profesionales para su evaluación científica.

La contribución teórica de esta investigación ha sido el descubrimiento de problemas en el modelado HBIM que no habían sido especificados antes, beneficios del HBIM (por ejemplo, el uso de plataformas online, el filtrado de información en sistemas HBIM, la integración de la divulgación cultural con HBIM) y requerimientos para implementar HBIM en la práctica tales como la necesidad de un protocolo simple e intuitivo y de ofrecer entrenamiento específico a los agentes no técnicos. Las contribuciones prácticas al conocimiento han sido la creación del protocolo BIMlegacy con la lista de agentes patrimoniales y la integración de procesos tradicionales, el diseño de la plataforma BIMlegacy con la sincronización de la información en tiempo real que permite que los agentes no técnicos puedan participar activamente en los modelos HBIM, el uso de HBIM como una herramienta de gestión, y la aportación de información rigurosa volcada por profesionales a disposición del público generalista y de las comunidades locales.

RESUM

Els projectes d`arquitectura patrimonial comporten treballs col·laboratius entre diferents agents tals com arquitectes , enginyers ,arqueòlegs , historiadors, restauradors , propietaris , etc. Tradicionalment cada disciplina ha treballat de manera independent generant informació dispersa. El flux de treball en els projectes patrimonials presenta problemes relacionats amb la desorganització de processos, la dispersió d'informació i l'ús d'eines obsoletes. Diferents organitzacions promouen fer servir mètodes innovadors per a tractar de resoldre aquests problemes i fer del patrimoni cultural un motor de desenvolupament socioeconòmic. BIM (Building Information Modelling) s'ha postulat com una metodologia adequada per millorar la gestió del patrimoni arquitectònic. L'aplicació de BIM a construccions històriques, anomenada HBIM (Heritage Building Information Modelling), ha demostrat tenir múltiples avantatges per gestionar projectes patrimonials. No obstant això, la literatura científica posa de manifest la necessitat de seguir investigant en els processos dels projectes patrimonials, la implementació pràctica de HBIM, la simplificació de la laboriosa tasca de modelatge HBIM i la documentació dels projectes HBIM.

L'objectiu d'aquesta investigació és el desenvolupament d'un protocol que ordeni la gestió de projectes patrimonials usant HBIM i el disseny d'una plataforma web que sincronitzi la informació patrimonial. DSR (Design Science Research) és el mètode d'investigació utilitzat per desenvolupar aquest protocol que ajudi a millorar el flux de treball en els projectes patrimonials. Les tècniques d'investigació utilitzades han estat l'anàlisi documental, entrevistes semi-estructurades i grups focals. També es van analitzar els processos HBIM i es van estudiar els requeriments dels agents patrimonials. HBIM es va proposar com el model virtual que acull la informació patrimonial i que articula els processos. Com a resultat, es va desenvolupar el protocol BIMlegacy, dividit en vuit fases, contemplant a tots els agents que participen en projectes patrimonials. Aquest protocol es va aplicar en el cas d'estudi real de Fixby Hall, edifici

històric a Huddersfield (Regne Unit), i els seus resultats van ser exposats en un workshop interdisciplinari per validar i millorar el protocol. Basat en aquest protocol, el grup de recerca va desenvolupar la plataforma BIMlegacy com a eina per poder dur a terme aquest flux de treball on agents interdisciplinaris poden unificar i sincronitzar la informació patrimonial. Aquest innovador sistema en el núvol connecta la base de dades intrínseca dels programes HBIM amb les bases de dades patrimonials fent servir un plug-in per Revit d'Autodesk, un web API, un servidor SQL i un portal web. La plataforma BIMlegacy es va dissenyar com un web de treball, però també com un web de difusió cultural on el públic generalista pot accedir a certa informació dels monuments. El protocol i la plataforma BIMlegacy van ser utilitzats per gestionar el projecte de Registre de Sant Joan de l'Hospital (Espanya). El protocol va ser exposat en un workshop a Huddersfield, Regne Unit, per a la seva avaluació amb professionals interdisciplinaris. Posteriorment, el protocol, la plataforma i els resultats del projecte de Sant Joan van ser exposats en un grup focal amb professionals per a la seva avaluació científica a València.

La contribució teòrica d'aquesta investigació ha estat el descobriment de problemes en el modelatge HBIM que mai havien estat especificats abans, beneficis del HBIM (per exemple l'ús de plataformes en línia, el filtrat d'informació en sistemes HBIM, la integració de la divulgació cultural amb HBIM) i requeriments per implementar HBIM en la pràctica, com ara la necessitat d'un protocol intuïtiu i simple on oferir entrenament específic als agents no tècnics. Les contribucions pràctiques al coneixement han estat la creació del protocol BIMlegacy amb els agents patrimonials i la integració de processos tradicionals, el disseny de la plataforma BIMlegacy amb la sincronització de la informació a temps real que permet que els agents que no son tècnics puguin participar activament en els models HBIM, l'ús d'HBIM com una eina de gestió, i l'aportació d'informació rigorosa bolcada per professionals a disposició del públic generalista i de les comunitats locals.

Translated by Mr. Albert Dotras I Garriga

1 INTRODUCTION

This chapter provides an introduction to this research which addresses the application of BIM to heritage architecture. The research context addresses the importance of heritage projects to enhance the local economy and the demands to heritage organisation to have more efficient management systems. The research problem is discussed standing the main uses in managing data in heritage buildings and the achievements of HBIM. The aim and objectives of the research are presented as conclusion of the argumentation. The contribution to the body of knowledge is argued prior to a brief summary of the methodological approach adopted for the study. The structure of the entire thesis is offered last.

1.1 RESEARCH CONTEXT

1.1.1 RESEARCH TOPIC

This research focuses on the adoption of BIM in heritage architecture. Heritage architecture has management problems that results in inefficiency with the sector, however the potential benefits of BIM could help improve productivity. The application of BIM to heritage architecture is recent, and the literature describes its potential benefits for the sector, such as the representation of historical phases or the benefits of BIM databases (Xiong *et al.*, 2013). However, HBIM requires further study as it does not take into sufficient consideration the cultural legacy of the buildings, heritage stakeholders or cultural regulations (Ilter and Ergen, 2015). It is proposed to develop a HBIM protocol and a web-based platform, both named BIMlegacy.

1.1.2 HERITAGE PROJECTS TO ENHANCE THE ECONOMY

Humankind needs to ensure the legacy of historic buildings to subsequent generations. The concern for heritage preservation has increased and has been regulated by international, state, and local standards as well as master plans. These regulations promote an appropriate building preservation, respect for the cultural landscape, and sustainable information access (Naeyer *et al.*, 2000).

Heritage architecture sector is very important for the country’s economy, tourism, and the legacy of societies. Heritage architecture has particularities when comparing with new construction such as that it should be documented, and its rigorous preservation is regulated by international organisations and charters, countries laws, and local regulations (Naeyer *et al.*, 2000).

The number of buildings with heritage recognitions around the world, Europe and Spain is increasing. Europe has incredible heritage richness: it has 453 sites recorded in the UNESCO list of world heritage sites. Spain is the third country in the world with more sites declared World Cultural Heritage by UNESCO (2013).

The need for new technologies to manage heritage interventions is further highlighted by the fact that there is an increasing number of heritage buildings needing restoration work in cities across Europe (Naeyer *et al.*, 2000). Interventions in existing buildings represent a high percentage in the total construction industry. For instance, in Spain refurbishments represented 55.7% of the total of construction sector in 2016 according to the Ministry of Competitiveness (Ministerio de Competitividad, 2016). This large percentage of refurbishments support the idea that the rehabilitation of existing buildings is becoming an important economic engine (Girard and Gravagnuolo, 2017). This quantitative information is presented to justify the future market and usefulness of the protocol and platform that was developed within this research.

Heritage preservation assumes a fundamental role in the process of sustainable development (Almeida *et al.*, 2018). Heritage represents a resource that can enhance territorial multidimensional productivity, producing economic, social and environmental value (Girard and Gravagnuolo, 2017). Cultural tourism is a brilliant opportunity for sustainable economic development, and well-preserved heritage buildings are fundamental to enable this. The conservation of historical buildings is usually supported by local citizens who feel attached due to their closer heritage. Hence, there is a need to develop solutions to improve the management of heritage projects (Brumana *et al.*, 2013; Eppich and Chabbi, 2007).

1.1.3 HERITAGE ORGANIZATIONS DEMAND MORE EFFICIENT MANAGEMENT SYSTEMS

There is an increasing interest in the adoption of new methodologies by heritage organisations and work groups, which aim to improve heritage inefficiencies further explained in section 1.3 (Perng *et al.*, 2007; Kempton, 2006). Many international polices such as the Horizon 2020-European Commission, the architectural technical regulations (Antonopoulou and Bryan, 2017), and different international conservation councils (Maxwell, 2016, 2014), highlight the need for collaborative systems which enables improved information sharing in heritage building projects. The AGI Foresight Report 2020 (2015) proposes the use of modern technologies to monitor infrastructures aiming to foresee any possible maintenance problem (Ellul and Wong, 2015). These views are also shared by HBIM researchers from different countries and specialities, e.g. Hernández, Dore and Murphy (2012); Brumana, et al. (2013); Arayici, et al. (2017).

The Spanish Ministry of Development established the BIM implementation in public buildings in August 2015 through the “Comisión BIM” by making BIM mandatory for public construction in two phases: December 2018 for architecture and July 2019 for infrastructures; while in United Kingdom (UK) BIM had already become mandatory for implementation on all public sector works in 2016. Many national historical buildings are publicly owned; and, therefore, they are affected by this regulation, having to use HBIM methodology (HM Government, 2012).

1.2 JUSTIFICATION OF THE RESEARCH

The creation of a heritage management protocol, as well as platform, is considered a necessity due to the dispersion of information around historic buildings.

In order to explain clearly what is meant by a platform and a protocol in this doctoral thesis, the definitions of both terms are exposed bellow:

- Protocol constitute the conceptualisation for specifying a solution of a previous defined problem shaped like a graphical representation of a sequence of movements or actions of people and things involved in a heritage activity.
- Platform is defined as a web-based application that run online, that are completely independent of the user's actual computer operating system.

Different heritage regulations demand appropriate management database systems for building preservation (Naeyer *et al.*, 2000), and productive management database systems for these monuments (Volk *et al.*, 2014). The large amount of heritage buildings increases the need of efficient systems to manage heritage projects because interventions in heritage buildings suppose an important economic engine to local economies (Girard and Gravagnuolo, 2017).The use of innovative systems, as HBIM, may help to improve the productivity of heritage project; thus, the research and creation of a protocol and platform is justified.

HBIM may help to improve the productivity of heritage project for the following reasons that will be further explained in section 2.5:

- The capability to represent all the historic-constructive phases of the building in one single 3D model (Oreni *et al.*, 2014).
- The synchronisation of information in real time (Quattrini *et al.*, 2015).
- The creation of libraries of historic constructive items (Antonopoulou and Bryan, 2017).
- The possibility of reducing errors since information can be updated in real time (Oreni *et al.*, 2014).
- With HBIM the quality of projects tends to be higher and the economic cost of the projects is equivalent to other projects (Migilinskas *et al.*, 2013).
- The project and construction time are shorter when developing a project with BIM given that stakeholders and consultants can see each other’s work as it is developed (Volk *et al.*, 2014).
- HBIM reduces the changes during the construction phase as the virtual pre-construction allows contractors and engineers to foresee any possible mistakes or risks (Hu and Zhang, 2011).
- HBIM gives clients a clear understanding of the space use through 3D visualisation (Zekavat *et al.*, 2014).
- HBIM can facilitate the maintenance and use management of historical monuments in terms of preventive maintenance (Salvador García *et al.*, 2018).

1.3 THE RESEARCH PROBLEM

Considering the above, this investigation entails a problem with practical importance and theoretical relevance; the main issues in managing heritage buildings intervention and the HBIM scope are discussed next. There are significant inefficiencies on heritage architecture interventions, e.g. conservation, rehabilitation, restoration, and reconstruction (Arayici *et al.*, 2017). These inefficiencies lead to high costs in the conservation of heritage buildings compromising the preservation of cultural heritage.

Many stakeholders with a variety of backgrounds are involved in heritage intervention projects, e.g. archaeologist, archivist, structural engineer and restorer (Garagnani *et al.*, 2016). These stakeholders usually work separately, and therefore dispersed data is produced (González-Varas Ibáñez, 2000), sometimes duplicating work or not taking into consideration existing information or other stakeholders' contributions (Migilinskas *et al.*, 2013). For example, the architect may research the history of the building without considering the archivist or historian's work previously generated. This practice may affect the project outcome because two stakeholders perform exactly the same work which end up duplicating project costs unnecessary.

The use of unconnected protocols and divergent techniques contribute to this dispersion of information. Modern technologies such as 3D systems and laser scanning for surveys are occasionally used in heritage buildings (Garagnani *et al.*, 2016). However, these techniques tend to be used just to support specific tasks, and many times these are unconnected with the general purpose of the project (Xiong *et al.*, 2013). Furthermore, traditional methods and files are used, which produces diverging data that hinders interoperability (Forster and Kayan, 2009). These ineffective work practices result in economic losses and consequently the distrust of historic project management (Volk *et al.*, 2014); as a consequence there are insecurities in costs and schedules for real estate or property developers when developing a historic refurbishment or intervention (Teo and Loosemore, 2001). Such insecurities could increase construction costs due to the impossibility to spot 'clashes' (Clash detection is a process of checking collisions and interferences within multiple disciplines of building) at an early stage in the project.

HBIM can be a solution for some of those problems due to their proven benefits in heritage projects (Brumana *et al.*, 2013). However, HBIM still requires further study because it does not always take into account the social and cultural needs, which is a fundamental requirement in heritage projects (Arayici *et al.*, 2017; Volk *et al.*, 2014), as it is further discussed in the literature synthesis in sections 2.5, 2.6, and 2.7.

1.4 AIM AND OBJECTIVES

The aim of this research is to propose a HBIM protocol to manage interventions in heritage buildings, including all stakeholders involved, as well as the design of a HBIM web platform to facilitate the information sharing between interdisciplinary stakeholders.

The specific objectives are:

1. To understand the stakeholders' needs in heritage interventions and to study processes in heritage architecture projects.
2. To identify the factual issues of HBIM application and the existing HBIM protocols and platforms.
3. To develop the solution, as follows:
   - 3.1. Proposing a protocol (BIMlegacy) for managing the interventions in historical buildings with HBIM.
   - 3.2. Designing a web platform prototype (BIMlegacy) that synchronises heritage information.
   - 3.3. Applying the protocol and the platform to two case studies.
4. To evaluate BIMlegacy protocol and BIMlegacy platform with professionals through a workshop and a focus group.

In this research, managing historical building projects involves recording the existing historic building information, modelling the existing building and information, designing the intervention (e.g. refurbishment), developing construction works, and planning the preservation of the monument. A multidisciplinary approach to the process is taken in this research.

1.5 CONTRIBUTION TO THE BODY OF KNOWLEDGE

This research contributes to the knowledge in a theoretical and a practical way.

The main theoretical contributions are:

- HBIM issues: modelling issues in representing the wall stratigraphy, pathologies, and sculptures or complex shapes (a.e. cornices and scrollwork).
- HBIM benefits: use of online platforms to assist HBIM implementation, sophisticated modelling to determinate a correct intervention criterion, filtering the information in HBIM database systems, the integration of cultural promotion and preservation tradition within HBIM and the advantage of representing the wall stratigraphy with BIM phases.
- HBIM needs: importance to have a simple and intuitive protocol to be useful, and **specific training** for **non-designer stakeholders** to understand the technology potential.

The main practical contributions are:

- An overall protocol to be used by HBIM stakeholders (a.e. architect, archaeologist, restorer, contractor, etc.) that will help them to know the BIM tasks required in each phase of the life cycle and the stakeholders involved. The protocol will guide heritage professionals who want to adopt HBIM to better perform HBIM steps. A complete list of heritage stakeholders and the integration of the traditional heritage processes in the BIMlegacy protocol are contributions as well as BIMlegacy easiness of use and simplicity in practice. BIMlegacy protocol helps non-technical stakeholders to be active within the HBIM process without having to use complicated modelling software. They can easily provide inputs to the process.

- An innovative HBIM platform where heritage stakeholders could share information and work in real time. Nowadays, there isn`t any system to synchronise HBIM information, it is because this platform is innovative. It solves problems of synchronisation and unification of information in real time, which could not be done before allowing technical stakeholders and non-technical stakeholders to work together effectively.
- The society will benefit from BIMlegacy since the rigorous information uploaded by professionals will be accessible to the public. The representation of the constructive-historic hypothesis is useful to promote the cultural diffusion.

The benefits of the adoption of BIMlegacy protocol by heritage stakeholders are that it provides clear guidance on how to adopt HBIM and highlights the human and material resources that are required. Furthermore, the use of the BIMlegacy platform will support sharing of information, control of changes during the project in heritage architecture (heritage projects can be preservation, conservation, full intervention or rehabilitation; those concepts are further explained in sections 2.1 and 2.2), the up-front accuracy of the project costs, and the contemplation of all the stages of the life cycle, further explained in sections 4.4.1 and 4.4.2.

1.6 BRIEF DESCRIPTION OF THE METHODOLOGICAL APPROACH

This work uses Design Science Research (DSR) as the methodological approach to develop a protocol and platform to improve the workflow in the heritage interdisciplinary projects. Within this approach, research techniques used include documentary analysis, case studies, semi-structured interviews and focus groups.

DSR is a research approach that focuses on the development and performance of artefacts with the explicit intention of improving the functional performance of the artefact. In DSR, as opposed to explanatory science research, academic research objectives are of a more pragmatic nature (Holmström *et al.*, 2009). DSR was chosen as a research method for the following reasons: (1) the research problem is practical, but it also has theoretical relevance, and (2) an artefact was developed as an output. Both reasons are linked to the main aims of DSR as a methodological approach.

The research was divided into five stages (Peffers, Tuunanen, Rothenberger, and Chatterjee (2007): (1) identify the problem, (2) define objectives, (3) design the solution, (4) implement the solution, and (5) evaluate the solution. The investigation included three chronological iterative phases that follow the five stages previously described. The research design is further explained in section 3.2.3.

1.7 STRUCTURE OF THE THESIS

Chapter 1 Introduction

This chapter outlined the research problem, detailed its aims and objectives and provided a background to its study and an overview of the research methodology. It provided a summary of the key findings and the research contribution to knowledge.

Chapter 2 Literature synthesis

This chapter critically reviews the literature related to this research and provides a background to the heritage architecture and its problems and reviews HBIM to confront these challenges.

Chapter 3 Research method

This chapter presents and develops the research method. It discusses the research philosophy, methodological choices and approaches and provides a comprehensive justification for the approach and methods adopted for this research. It discusses the proposed research samples and the proposed organisation of collecting data along with methods of synthesis and analysis. Finally, this chapter presents its journey of ethical compliance.

Chapter 4 Data analysis

Results section presents the research findings of the research that are: the identification of the monument management needs; the results of both case studies, Fixby Hall and San Juan; the description of BIMlegacy protocol and all their steps; and the description of the HBIM platform. After explaining and analysing the results (for each phase) there is a sub-section on the validation of the protocol and the web platform.

Discussion section presents the discussion of findings and the basis for the framework development. It takes into consideration the relevance of the findings from which it develops a HBIM protocol and an HBIM platform.

Chapter 5 Conclusions

This chapter offers conclusions, achievements of goals, recommendations, limitations, and future lines of research. It summarises the achievement of the research aims and its objectives, justifying its conclusions and contribution to knowledge in this field and it also offers recommendations for further research.

2 LITERATURE SYNTHESIS

The purpose of this section is, on the one hand, to gain an understanding of the existing research and debates relevant to existing buildings and heritage preservation needs, BIM, HBIM, and HBIM protocols and platforms, and on the other hand, to state the literature gap and the specific HBIM areas that require further study.

The state of the art study was conducted through a systematic literature review method and its subsequent analysis (Osterweil, 2006). The literature review was performed through five steps: (1) preliminary approach and initial tests; (2) literature search; (3) classification of papers considering quantitative and qualitative analysis; (4) exploitation and analysis of results; and (5) summary of main contributions and in-depth study of the most relevant papers (García Valldecabres *et al.*, 2016). These steps are further explained in section 3.2.3.

2.1 EXISTING BUILDINGS AND HERITAGE BUILDINGS

According to Historical England and the Department for Communities and Local Government of United Kingdom the definition of heritage architecture is: "A building, monument, site, place, area or landscape identified as having a degree of significance meriting consideration in planning decisions, because of its heritage interest." (Department for Communities and Local Government of United Kingdom, 2012).

There are various levels of protection from the World Heritage and the European Cultural Heritage to the Historic Patrimony of Spain or Heritage England at a more immediate or local level. The Cultural World Heritage comprises a list of buildings and assets with cultural and natural values of extraordinary universal value upon the Cultural World Heritage Committee of the United Nations Educational, Scientific and Cultural Organization (UNESCO 2013).

The European Cultural Heritage consist of many cities, landscapes, and archaeological spaces. It contributes with the sustainable, economic, and social development (García *et al.*, 2007) of countries and it is tie to History and common values (Ministerio de Cultura y Deporte, 2018).

The Historic Patrimony of Spain is composed of assets and objects of artistic, historic, paleontological, archaeological, ethnographic, scientific, and technical interest. Heritage documents and bibliography of artistic or anthropological interest are also part of the Spanish Patrimony as well as the intangible heritage (Spanish Ministry of Presidency and Territory, 25 de junio de 1985).

There are categories among the existing buildings and sites valuing their cultural values, antiquity or artistic importance. They are categorised depending on the country or state; generally, they include common recent existing buildings, catalogued buildings with protected areas, and heritage buildings that are clearly protected (Eppich and Chabbi, 2007). Heritage can be public; owned by the Crown, the State, the Autonomous Regions or City Halls; or private; owned by the Church or a private organisation or person.

This research focuses on private medium size protected buildings because they represent the most common typology in Europe and these kind of buildings usually have less economic resources to use new technologies in their projects than important public monuments so they need it more. The difference between common existing buildings and heritage ones is that heritage projects involve architectural, historic and archaeological documentation, so it involves the technical reproduction of a context, as well as an intellectual effort to describe the socio-cultural heritage setting (Gazzola *et al.*, 1964).

2.2 HERITAGE PRESERVATION

Historic buildings and sites should be preserved as cultural legacy and common heritage (Gazzola *et al.*, 1964). Heritage preservation has a technical dimension because historical buildings should be physically preserved and a social dimension since heritage should be broadcasted within society to assure its protection (Naeyer *et al.*, 2000).

The Nara Document on authenticity (1994) defines preservation as "all efforts designed to understand cultural heritage, know its history and meaning, ensure its material is safeguarded as required and its presentation, restored and enhanced. Cultural heritage is understood to include monuments, groups of buildings and sites of cultural value as defined in article one of the World Heritage Convention" (World Heritage Committee and ICOMOS, 1994).

Responsibility for cultural heritage and the management of it lies with the cultural community that has generated it, and subsequently to that which cares for it. (World Heritage Committee and ICOMOS, 1994). The Law 16/1985 of the Historic Patrimony of Spain states that the Spanish State Administration must grant the Historic Heritage Preservation as well as promote its divulgation within the society. Local Governments must cooperate with the Preservation Departments of the Spanish State. This law also promotes the exploitation of heritage sites through their actions and own promotion. It encourages the divulgation of heritage within society and the utilisation of heritage buildings by local citizens (Spanish Ministry of Presidency and Territory, 25 de junio de 1985).

The International Restoration Charts, even though in some European countries such as Spain are not mandatory, have stabilised the adequate preservation criteria. The Athens Charter for the Restoration of Historic Monuments (1931) was the first international document regulating restoration and preservation of historical patrimony. The Venice Charter (1964) continued with the concepts of the Athens Charter and introduced the terms "historic sites" and "modest works" and gave importance to colour, scale and volume. The *Carta di Restauro* (1972) became mandatory in Italy and incorporated the stylistic unity and were obligated to mark the different between the original pieces and the reconstructed ones (Marconi, 1993). The Charter of Krakow is the most recent document defining the principles for conservation and restoration of built heritage. It introduced the training and education in heritage and the concept of historic towns and villages. (Naeyer *et al.*, 2000).

The UNESCO (2003) presented the Guidelines for the Preservation of Digital Heritage to ensure that it remains permanently accessible. Accordingly, access to digital heritage materials, especially those in the public domain, should be equitable and free of unreasonable restrictions (Webb, 2003).

ICOMOS (1990) in its Guide to Recording Historic Buildings concluded that the registration of an historic site must include not just the building itself (materials, structure, pathologies) but its significance and values. (International Council on Monuments and Sites, 1990). According to Worthing (1999) the historical site registration is not an isolated event but a continuous process and it is the previous requisite to perform further actions in the project or construction (Worthing and Counsell, 1999).

Preventive conservation is considered very important to preserve heritage architecture. According to the *Plan Nacional de Conservación Preventiva*, "the preventive heritage conservation plan, is a strategy proposing a systematic methodology to identify, evaluate, detect, and control risks associated with activities and events that can deteriorate the building". The objective is to eliminate or minimise these risks confronting the problems at their source, what usually is an external factor. To perform a good preventing conservation, it is extremely important to monitor the building deterioration and prevent the loss of constructive elements avoiding expensive and drastic restoration actions (Ministerio de Cultura y Deporte del Gobierno de España, 2015).

In conclusion, HBIM methodology must consider all this knowledge and regulations elaborated with major consensus and respected by heritage stakeholders.

2.3 BUILDING INFORMATION MODELING (BIM)

ISO Standards defined BIM as "shared digital representation of physical and functional characteristics of any built object […] which forms a reliable basis for decisions" (Standard I. S.O., 2010). Cabinet Office of the UK government publication defines BIM as the process of generating and managing information of buildings and sites over the years or the building's life-cycle (Great Britain, 2013)p.6). The most recent definition of BIM by the UK Government is "a collaborative way of working, underpinned by the digital technologies which unlock more efficient methods of designing, delivering and maintaining physical built assets. BIM embeds key products and asset data in a 3D computer model that can be used for effective management of information throughout an assets lifecycle" (Architectural, Engineering and Construction (AEC) Initiative, 2015). With this definition, BIM has evolved into a more open concept since it takes into consideration the management of the whole lifecycle of the buildings, and this is the BIM concept that is been considered in this thesis.

Building Information Modelling has been recognised as the most important transformation in the construction industry related with the Technology Information (TI). However, it took philosophical ideas from previous methodologies. Numerous investigations affirm that BIM and Lean Construction have many principles in common (Sacks *et al.*, 2010). BIM could be a processual and technological approach that supports Lean construction concepts (Dave *et al.*, 2013).

BIM has been successfully adopted in new buildings, supporting sustainable architecture (Jeong *et al.*, 2016; Inyim *et al.*, 2014), facilities, and structures (Barnes and Davies, 2015). Gu et al. (2010) stood that the factors affecting how BIM is adopted by industry are: the necessities, the work processes, the resources and the technical tools (Gu and London, 2010). Eadie (2013) agreed in the importance of the technology for the BIM adoption in the construction industry. This study confirms that BIM is utilised more in the first stages of the life cycle and progressively BIM is used less. Also, they detected a lack of communication between the team and the client, and between work team members (Eadie *et al.*, 2013).

Nevertheless, the literature shows that processes and human resources related to BIM still need further study (Sackey *et al.*, 2014; Coates *et al.*, 2010). Interoperability still been an issue even though Building Smart (2014) launched the second generation of BIM Collaboration Format (BCF) as the open code to tag semantic information (Barnes and Davies, 2015; Kiviniemi *et al.*, 2008).

Research on BIM is becoming more specialised and it usually focus on a single aspect of BIM. Different branches of BIM are described below:

BIM Management is one of the most active fields of engineering. It has been developing aspects such as 4D Time, 5D Costs and Expenses, 6D Energy Efficiency, and 7D Maintenance (Díaz Vilariño *et al.*, 2017). Besides, BIM has been applied with remarkable success to architecture and construction related fields such as construction monitoring and environmental impact among others (BIM International conference, 2013). Design with BIM has been studied from different perspectives. Hernandez studied Studying the BIM as a tool to design, that allows controlling and representing complex shapes, this will evolve the architectural form. He analysed the connectivity of BIM technology, the development of implementation projects and the requirements of existing legislation, which involves simulating virtual buildings (Agustín Hernández, 2011).

Level of Development (LOD) of BIM projects require further study for specific areas. Thus, different studied have examined the impacts of BIM maturity on project performance (Lee and Kim, 2017; Smits *et al.*, 2017). ‘Level of definition’ is defined in PAS 1192-2 as the “collective term used for and including ‘level if model detail’ and the ‘level of information detail’”. ‘Level of model detail’ is the description of graphical content on models at each of the stages defined, for example, in the CIC scope of services. The ‘level of model information’ is the description of non-graphical content in models at each of these stages. BS 8541 defines level of detail for BIM objects as (1) schematic, (2) concept, and (3) defined. BS 8541-3 is the code of practice for the shape and measurement of BIM objects. Some studies have research in simulations to improve certain behaviours in the construction sector. Shan and Goodrom studied the Impact of temperature and humidity at the project level in steel structures using BIM and Critical Path Method Schedules. Their contribution was to provide a framework that can help practitioners better understand the overall impact of a productivity influencing factor at a project level, in order to facilitate better decision making (Shan and Goodrum, 2014).

Furthermore, the Information and Communications Technology (ICT) to BIM and BIM to Mobile Augmented Reality (MAR) are useful for publicity purposes, but both are still underdeveloped and at a theoretical level; the need for connection between 3D models and online platforms to share BIM data is exposed. Synchronization of BIM with MAR is a promising BIM developing area. BIM2Mar is an efficient solution to integrate the geometry and the data of the models in a MAR so data is automatically updated, accessible in real time (Williams *et al.*, 2014).

Social Factor in BIM is the key for productivity, and it highlights the urgency for further research on the human aspect; hence, elements that would improve the BIM system were noted. For instance, negotiations of action plans, creation of dictionaries for specific terms, and creation of technologies that support the conversation and resolution of interdisciplinary problems (Zekavat *et al.*, 2014).

Scan to BIM was initially developed by private laser scanning enterprises within the computer industry (Xiong *et al.*, 2013). Currently, the most advanced applications turn some of the cloud data points into BIM elements, but this conversion is imprecise especially when applied to historical architectures that have more irregular shapes. Besides the Scan to BIM models, there are also textured cloud points models, but they do not correspond to a virtual construction mode. The textured cloud points models process the images and drawings and create the mesh surfaces (Bosché *et al.*, 2015).

BIM technology has evolved considerably during the past few years. This study confirms that BIM is utilised more in the first stages of the life cycle and less during construction and maintenance.

2.4 EXISTING BUILDING INFORMATION MODELING (EBIM)

While BIM processes are established for new buildings, most of existing buildings are not maintained, refurbished or deconstructed with BIM yet (Volk *et al.*, 2014). BIM for existing buildings (eBIM) raised as the methodology to manage and maintain existing buildings with BIM methodology BIM models for existing buildings must focus in the management, maintenance, and use (Edwards, 2017). The application of BIM to existing buildings is recent but there is an increasing interest in the area, especially for maintenance and large refurbishments (Xiong *et al.*, 2013).

Edwards (2017) argues that many buildings are not correctly managed or maintained for the following reasons: lack of knowledge and experience, lack of resources, and dependence on other stakeholders (Edwards, 2017). In recent years, some international organisations, such as the Government Service Administration, have used BIM to manage existing buildings and to control maintenance and MandE systems (GSA, 2013, cited in (Arayici *et al.*, 2017), p. 9).

BIM provides great benefits for existing buildings: (1) all data is archived in the same repository, (2) the exact location of MandE systems and all their information is controlled, (3) maintenance information such as services, refill data, and material specifications are contained in one single file. However, all these benefits are at a high economic cost (Edwards, 2017).

Despite fast developments and the BIM standards, challenging research opportunities arise from process automation and BIM adaption to existing buildings' requirements (Volk *et al.*, 2014) as well as making EBIM models useful to manage energy efficiency and sustainability (Edwards, 2017).

2.5 HERITAGE BUILDING INFORMATION MODELING (HBIM)

Murphy et al. (2009) defined HBIM as a new system of modelling historic structures creating full 2D and 3D models, which include detail behind the surface of the objects concerning its methods of construction and material makeup. According to Volk el al. (2014) HBIM is the dynamic database of a historic building with an improved coordination of construction documents, in which geometry, spatial relationships, geographic information, and other quantities or properties of building components are structured and documented. HBIM has been recently defined as the recording and modelling of existing buildings, generating BIM geometry from point clouds (Dore and Murphy, 2017)

HBIM investigation started around 2007 but it seemed to be in a very early stage of development. It focused mainly in the architectonic survey or building registration through point clouds (Penttilä, 2007). Schill et al. (2007) in his 'Virtual Environmental Planning systems' (VEP) developed an interface that allowed the releasing of heritage videos and the visualising of the 3D model. This system was designed with static digital pictures, so that it could incorporate old historic photography (Schiller and Mandviwalla, 2007).

Murphy et al. (2009) started by studying the way to adapt the parametric objects to the point cloud. Subsequent studies showed the necessity of combining 3D models in a 3D GIS file to improve the targeting of the semantic information. There are many investigations focusing on solving this problem, however, they could not yet find an automatic proposal that resolves this problem (Murphy *et al.*, 2009).

Fai et al. (2011) used Navisowrks software from Autodesk to fuse data coming from various sources and geo-referencing the semantic targets of intangible heritage and their digital reconstructions. They affirmed that HBIM requires further study and they highlight the importance of registering historical buildings not just with quantitative data but also with qualitative data such as historical photography, oral feedback, and vernacular music (Fai *et al.*, 2011). The UNESCO (2001) stabilised the “qualitative indicators” of the intangible cultural patrimony that are language, music, religious ceremonies, traditional constructive techniques, games, and dance. Then, the UNESCO (2013) identified the necessity of recording and archiving digital material such as texts, databases, static and dynamic images for future generation’s disposal (Labadi, 2013).

Dore and Murpy (2012) developed an architectonic parametric library starting from old architecture books from the c. XVIII, for that, “geometric descriptive language” (GDL) of ArchiCad software of Graphisoft company was required. They modelled a complete building, including the detailed system and the constructive material (Dore and Murphy, 2012). The relevance of this research from a perspective of managing heritage project using HBIM resides in the standardization of objects in a library which supposed a contribution to practice in HBIM.

Oreni (2014) created an HBIM model with linked information related with materials, stratigraphy, geometrical data, and historic data. These HBIM models are a useful instrument to archive and access the information remotely. This information was used in preventive maintenance, interventions, and restoration of built heritage (Oreni *et al.*, 2014). This research was one of the first investigations linking external databases with HBIM models.

Fassi (2011) proposed the use of HBIM to manage maintenance operations during all the life-cycle of the building (Fassi *et al.*, 2015). The Opera House management project in Sydney was developed with HBIM to order all the building information and grant an effective management of this complex patrimony, which projected an expecting lifespan of 250-300 years (Linning *et al.*, 2016). HBIM was used until this moment in the project phase but these researches contributed to apply HBIM to the maintenance phase.

Maxwell (2014) highlighted that different interventions in heritage buildings (a.e. restoration, maintenance, reconstruction) require different registration techniques. He also argued that the historical buildings surroundings must be protected and registered within HBIM methodology (Maxwell, 2014). Volk et al. (2014) stated that BIM implementation in existing buildings is scarce, needing improvements in conversion point clouds to BIM models, updating data in BIM, and modelling items and relations in existing structures. This research, in contrast to other HBIM sources, stated that detailed documentation of architectural heritage, the last and most important point, is the ultimate aim of the HBIM process.

Bosché et al. (2015) developed an algorithm that detects masonry surfaces from a point cloud. However, that system was not very successful and the same year. Also, Quattrini et al. (2015) supported the scanner laser technology to help BIM modelling to create high quality HBIM models. Garagnani et al. (2016) proposed the parametric modelling of complex geometry over the point cloud using a Revit plug in named GreenSpider. The relevance of these sources from a perspective of improving heritage projects resides on the incorporation of point clouds within HBIM models.

These projects entailed very complex modelling thus, the Durable Architectural Knoledge (DURAARK) project (2016) suggested simplifying the current complex modelling process by making BIM semantic models much simpler and even generating them from the point cloud (Lindlar and Tamke, 2014). The DURAARK is an interdisciplinary project which researches and develops processes and methods for the digital preservation of architectural three dimensional data. This project contributed with the body of knowledge with better understanding of the stakeholders' involvement in the process and of the implications that their involvement has on preservation decisions project. The DURAARK researchers stand that simple modelling has benefits such as the better understanding of the model by all stakeholders and the lower size of the files.

The application of HBIM until 2015 did not take into consideration the historical and cultural legacy of the buildings and sites (Ilter and Ergen, 2015). Lo Turco et al. (2016) highlighted the potential of HBIM as operative methodology for knowledge and management of cultural heritage. Baik (2017) agrees that BIM provides notable benefits for the comprehension of historical buildings and their context, as well as the material knowledge and the constructive techniques (Baik, 2017).

Casu and Pisu (2016) investigated the use of BIM for documentation and virtual reconstruction of lost heritage. They have followed the criteria of the London Charter (2009) for the computer-based visualisation of cultural heritage. From historical drawings and information of similar buildings they could create a library of architectonic elements and virtual families with descriptive and dimensional parameters (Denard, 2009) .

The R and D project financed by the Spanish Ministry of Economy and Competitiveness entitled: "Design of a Database, Management Model for the Information and Knowledge of Architectural Heritage (HAR2013-41614-R)", which frames this doctoral thesis, gave as a result the connection between historical databases and BIM databases for the first time, which is a major advancement (García Valldecabres *et al.*, 2016). Also, HBIM templates were created containing HBIM families, historical phases, and heritage materials to support future heritage groups interested in using this platform.

Recently, HBIM was also named Heritage Building Information Modelling, a broader term that includes historical data, conservation policies, and significance values. Heritage BIM includes highly protected buildings that usually require broader intervention projects and careful life cycle management. Dore and Murphy proposed six HBIM elements: heritage documentation standards, data collection techniques, 3D modelling concepts, as-built BIM, and procedural modelling (Dore and Murphy, 2017). Littlefield (2017) denominates HBIM as Heritage Building Information Modelling/Management. HBIM allows the future management of built heritage (Littlefield, 2017).

Studying heritage sites involves a multiple group of stakeholders: from architect to public administration. Heritage stakeholders stand that HBIM studies must take into consideration not only the technical stakeholders, but also non-technical stakeholders (Mansir *et al.*, 2016).

HBIM models with semantic information improve the knowledge of the constructive system but too much information added to the model could be counterproductive (Yalcinkaya and Singh, 2015). The kind of information included in the BIM models depends on their future use, that is, what is required out of this model.

HBIM is been used mainly for the buildings' graphic survey (Brumana *et al.*, 2013) but not to make a complete **management** model (Arayici *et al.*, 2017). Management involves the entire construction life which represents the most important advance because until now, HBIM was just used for graphic surveys. The absence of scientific publications with HBIM's practical enforcement supports the objectives of this doctoral thesis.

Some studies show that HBIM has been adapted to specific architectonic styles. Baik (2017) developed a HBIM architectonic library of Jewish elements adapted to the level of development (LOD), the style, shape, and similarities (Baik, 2017).

HBIM needs to develop specific LOD levels adapted to historical buildings necessities. Baik and Boehm (2017) suggested that there is limited information regarding the LOD necessary to develop HBIM models out of laser scanning and photogrammetry HBIM modelling, especially the existing condition of the construction (as built) with has a high LOD (Baik and Boehm, 2017).

Marzouk and Hawas proposed the use of HBIM as a documentation tool for scientific research and analysis. In addition, they highlighted that improvements in preservation maintenance are required (Marzouk and Hawas, 2017).

Other studies affirm that national heritage guides need to be taken into consideration for better HBIM approach. The Guidelines for Education and training in the conservation of Monuments, Ensembles and Sites (1993) should be considered in the HBIM implementation because it is a basic requirement for a respectful heritage preservation (ICOMOS, 1993).

HBIM has been further studied in countries such as United Kingdom (Department for Communities and Local Government of United Kingdom, 2012; HM Government, 2012), Spain (López *et al.*, 2017; García Valldecabres *et al.*, 2016) or Italy (Garagnani *et al.*, 2016; Oreni *et al.*, 2014). Italy has been working to change the construction industry through an innovation national project that consists in creating a free access HBIM database to share information between interdisciplinary professionals. They have developed 3D models from scanner laser and historic documentation linked in various case studies. Scianna (2014) developed a project to investigate the benefits and issues of BIM for archaeology, for the creation of archaeological 3D models integrated with databases using BIM models (Scianna *et al.*, 2014).

Aiming to rigorously register and preserve built heritage, Edwards (2017) proposed to include a guide of best practices in heritage conservation inside the HBIM models assisted with explicative videos and other sources of information as well as a verification list (Edwards, 2017). He also proposed to include the Guide to the Conservation of Historic Buildings BS 7913 in the HBIM models to complete the preservation and management of historic and traditional buildings (British Standards Institution, 2013). This guide, launched in 2013, recommends the use of HBIM, specifically in sections 5.7, 8.1 and 8.2.

- The 5.7 section remarks that large projects require more resources and skills to implement HBIM.
- The 8.1 section proposes to sensitise HBIM stakeholders to the heritage values and include them within the HBIM models.
- The 8.2 section revealed that quality control and supervision must be integrated in the HBIM models.

Counsell and Taylor (2017) specified that HBIM models must contain materials, structure, pathologies information, and how the use of the building reflects the social, environmental, cultural, and economic change. They also proposed to reuse this information to develop construction projects and to manage MandE maintenance. Digital HBIM repositories need to have filters and tools to analyse and visualise 3D the models. These repositories need to analyse the user web experience to have feedback and keep improving. Counsell and Taylor remarked that local communities must be involved to understand their necessities since the information must be available in the future centuries (Counsell and Taylor, 2017).

HBIM models are parametric and intelligent containing construction components and descriptive data, including thermic properties. Thus, HBIM models can be able to perform environmental simulations related with the energy consumption and airflow among others. This theoretical assumption helped to develop further practical studies (Häkkinen and Kiviniemi, 2008; Chaves *et al.*, 2015).

Cadw (2017) developed a project named Heritage Cottage related with energy efficiency of a heritage building in HBIM. This discipline has been named Green BIM (GBIM). In this project sensors were used to record real time data of the Heritage Cottage case study. Thus, information related with the isolation and the energy efficiency of walls and windows was recorded to add into the HBIM model. The analysis performed in this case study serve to have factual information instead of theoretical information. The study of these data allowed the development of intelligent systems to manage heritage preservation (Edwards, 2017).

The implementation of HBIM still requires methodological discussion and practical experimentation in order to apply this kind of documentation in a broader heritage conservation and maintenance process (López *et al.*, 2017). Some limits and barriers need to be investigated more extensively in the future with respect to the absence of freely available BIM assemblies and objects for heritage buildings (Brumana *et al.*, 2013; Fai and Rafeiro, 2014). With these challenges in mind, HBIM libraries require wide and shared research on drawings, elaboration, and interpretation activities of data survey (Oreni *et al.*, 2014).

There is a **knowledge gap in the BIM** technology's automation and adaptation to existing buildings because studies do not always take into account the social and cultural needs, which is a fundamental requirement in heritage projects (Arayici *et al.*, 2017; Volk *et al.*, 2014).

2.5.1 HBIM BENEFITS

The potential of BIM in the specific heritage context resides on:

- The capability to represent the historic phases in an integrated way (Megahed, 2015). With HBIM it is possible to have all the historic-constructive phases of the building in one single 3D model (Oreni *et al.*, 2014).
- BIM systems have an intrinsic computerised database that allows the synchronisation of information in real time with other specific field databases (Quattrini *et al.*, 2015).
- The creation of libraries of historic constructive items designed from historic manuscripts and architectural pattern books (Antonopoulou and Bryan, 2017).
- The possibility of performing structural and efficiency situations (Oreni *et al.*, 2014). HBIM can help to reduce errors since information can be updated in real time, and different stakeholders' work can be synchronised, reducing the potential of human error.
- All the historic, architectonic, archaeological, legal, environmental, and maintenance data of the historical buildings can be collected and synchronised as needed (Arayici *et al.*, 2017).
- With HBIM the quality of projects tends to be higher and the economic cost of the projects is equivalent to other projects (Migilinskas *et al.*, 2013). The standardisation of the constructive 3D elements enables easy sharing of information between all the stakeholders involved in the refurbishments. Once the 3D model is created, it is possible to automatically obtain all the sections, facades and floor plans, which reduce project elaboration time (Barnes and Davies, 2015).
- The project and construction time are shorter when developing a project with BIM given that stakeholders and consultants can see each other's work as it is developed, enabling them to share data and resources (Volk *et al.*, 2014).
- HBIM reduces the changes during the construction phase as the virtual pre-construction allows contractors and engineers to foresee any possible mistakes or risks (Hu and Zhang, 2011).
- HBIM gives clients a clear understanding of the space use through 3D visualisation. This feature enables clients to better understand the proposed design from its initial stages, and any possible design changes can be done before the construction phase. Traditionally, there were a lot of processes that the client was unaware of because they did not have access to this information or could not easily understand it. However, the 3D HBIM models facilitate decision making giving the client an in-depth understanding of the project (Zekavat *et al.*, 2014).
- HBIM can facilitate the maintenance and use management of historical monuments in terms of preventive maintenance and tourism exploitation of the building (Salvador García *et al.*, 2018).

2.5.2 HBIM ISSUES

Even though HBIM has proven to have notable advantages, there are a series of practical issues that simple HBIM could not solve (Volk *et al.*, 2014). BIM has been originally designed to support new buildings. This could make BIM adoption to heritage buildings challenging due to the specific characteristics of historic buildings (Barazzetti *et al.*, 2015). In addition, HBIM has been used mainly for maintenance and large refurbishments but its use for heritage buildings is limited. The results of HBIM case studies show issues related with the difficulty to model complex architecture with HBIM, to rightly document the historic buildings, and with the active participation of all interdisciplinary stakeholders (Garagnani *et al.*, 2016).

- Even though all proven benefits HBIM require a high economic cost for promoters and owners, the costs increase with the level of protection of a building (Edwards, 2017).
- Modelling historic structures is laborious, technically difficult, and time consuming due to the lack of BIM knowledge of heritage stakeholders and the complex characteristic of historic buildings (Barazzetti *et al.*, 2015).HBIM modelling can be too rigid to model organic and complex structures.
- Historians, restorers, and monument managers are not technically trained, which makes BIM modelling very difficult for them. Thus, they cannot fully participate within the HBIM process (Arayici *et al.*, 2017) .
- On another hand, historic buildings have an extended time of use that usually alters some of their features: repurposed structures, reused materials, and shape variations. They have complex shapes, which have gradually deteriorated. To model these degraded shapes is technically very difficult (Counsell and Taylor, 2017).
- Usually, each monument contains different architectonic styles (a.e. gothic, baroque). Historic buildings usually include a diversity of fabrics, several historic-constructive phases and sometimes pathologies such as cracks or humidity (Green and Dixon, 2016). Modelling all these architectonic styles and phases is laborious and technically difficult.
- HBIM case studies show that HBIM do not fully take into consideration the historical and cultural legacy of the buildings and sites (Ilter and Ergen, 2015). Most HBIM publications focus on the modelling and not much in the documentation. Historians and archivists, who usually perform the documentation in heritage projects, do not have the ability to manipulate HBIM models, which represent a handicap. (Dore and Murphy, 2017).
- Heritage stakeholders have different needs than those of regular Architecture, Engineering and Construction (AEC) professionals, and these need to be considered (Megahed, 2015). HBIM studies tend to focus on the architect point of view ignoring other stakeholders' requirements. For example, archaeologist may require tools to re-create disappeared volumes within a heritage project (Garagnani *et al.*, 2016).
- Educational protocols and guides to assist non-technical stakeholders are required (Zhao *et al.*, 2015).

Heritage organisations and government institutions promote investigations to solve those HBIM issues (Perng *et al.*, 2007). International framework programs, as the Horizon 2020-European Commission, architectural regulations, and different international conservation councils are promoting collaborative systems to enable better information sharing in heritage projects as well as more cultural diffusion within the society (Arayici *et al.*, 2017; Maxwell, 2016). Different researchers agree that protocols and guides to manage HBIM projects are very important, so that, next section presents a summary of the existing protocols methods and guides in the HBIM sector.

2.6 EXISTING HBIM PROTOCOLS, METHODS, AND GUIDES

Different HBIM guides and protocols have been proposed in the literature. Various frameworks and protocols for collaborative design processes have been developed to facilitate BIM implementation (Kassem *et al.*, 2014).These are briefly summarised below.

The finish COBIM (Common BIM Requirements 2012) drafted the first international guide for the effective elaboration of BIM models. Tulenheimo introduce and analyse the wide range of obstacles generated by customers, company's own organisation, social behaviour and immature technologies in Finnish construction engineering industry (Tulenheimo, 2015).

In 2012, the Royal Institute of British Architects (RIBA), published the RIBA outline plan of work including BIM, its levels of maturity and discussing its challenges (2012). In 2013, the Construction Industry Council published a BIM protocol with eight structured steps, Figure 1, as a response to the UK Government BIM Strategy (Construction Industry Council-CIC, 2013). It included definitions, Levels of Development (LOD), contract BIM statements, and a relation between the stakeholders and the steps of the protocol. Both documents focus on supporting the adoption of BIM in new buildings.

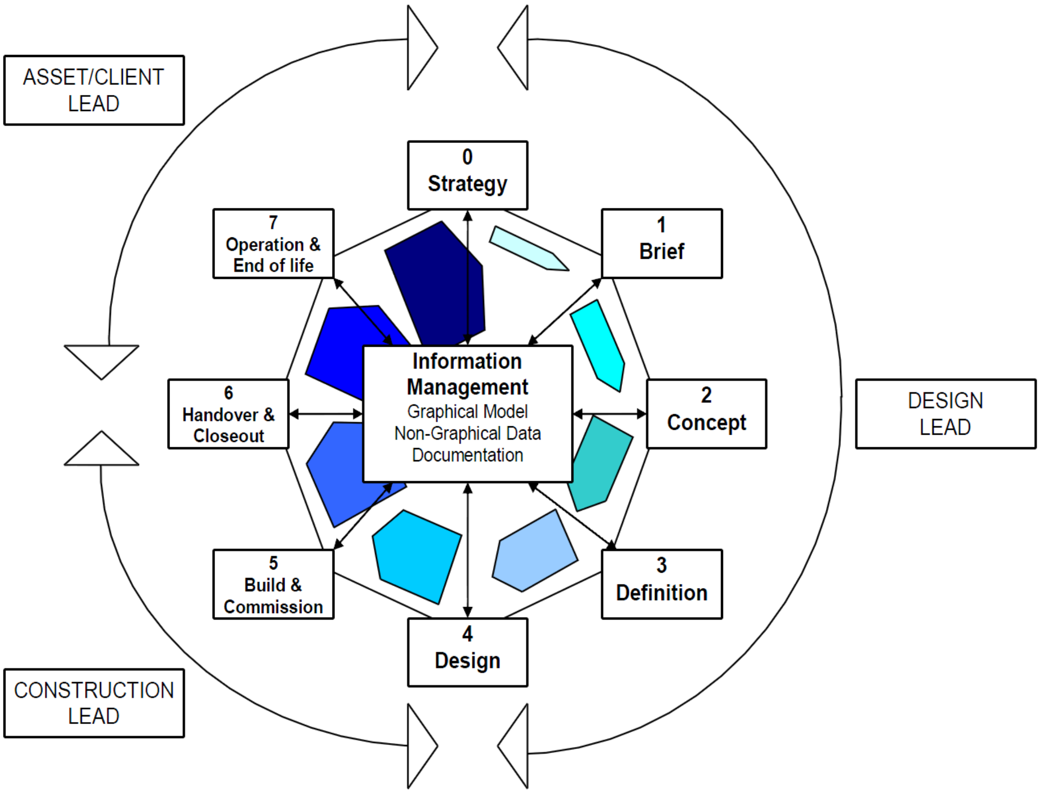


Figure 1. Construction Industry Council (CIC) BIM Cyclical Diagram (Construction Industry Council-CIC, 2013).

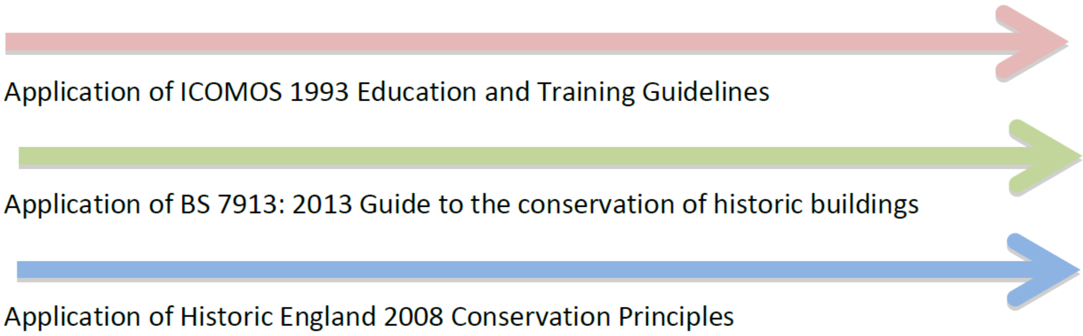


Figure 2. Construction Industry Council (CIC) BIM Cyclical Diagram has been used as reference flowchart to design the HBIM Method, 2013.

The guide to the conservation of historic buildings BS 7913 in the HBIM models to complete the preservation and management of historic and traditional buildings (British Standards Institution, 2013). This guide, launched in 2013, was considered to develop BIMlegacy protocol because of the following reasons:

- Explains how a heritage intervention must be evaluated.
- Describes the principles of heritage management and some critical advice. For example, the fact that interventions need to be as minimal as possible justifying any change.
- Proposes the inclusion of preservation politics and management plans in the HBIM models.
- Explains the kind of inspections that must be carried out in a heritage building, when these inspections need to be carried out, and who must perform these inspections.

- Reveals a holistic perspective for efficiency energetic and sustainability.
- Describes different strategies to improve the significance of the building and to improve its maintenance and management. Section 8.1 highlights the necessity of including heritage values within the HBIM model and that all stakeholders must consider these values.
- Demonstrate that large projects require more resources and skills to implement HBIM.
- Reveals that quality control and supervision must be integrated within the HBIM models.

The British Standards BS 7913 contains the requirements to manage and preserve historical buildings in United Kingdom. This report details what to be done and the competences of the different stakeholders. From the United Kingdom perspective, practicing the BS 7913 when working with HBIM is extremely important, as well as taken into consideration the international recommendations and the ICOMOS Charters. From other countries perspective, BS 7913 is adequate, but HBIM must put in practice the National Regulations (British Standards Institution, 2013).

In 2014 a multidisciplinary Spanish team composed of BIM experts adapted the finish guide to Spanish construction sector to grant the right use of BIM (Building Smart Spanish Chapter, 2014). The Spanish Ministry of Development constituted in 2015 the es.BIM Commission with the aim of pushing the BIM implementation in the construction industry. The es.BIM Commission has developed interesting reports out of the regular meetings and work groups such as the five report (esBIM commision, 2018).

The Conference on Training Architectural Conservation (COTAC) Report, 2014, summarised the outcomes of the three annual COTAC Conferences in relation to HBIM (Maxwell, 2014). It uses the CIC diagram, and overlaid the ICOMOS Education and Training Guidelines, as described in Figure 1. This model was further developed with the support of 5 international heritage organisations in 2016 (Maxwell, 2016).

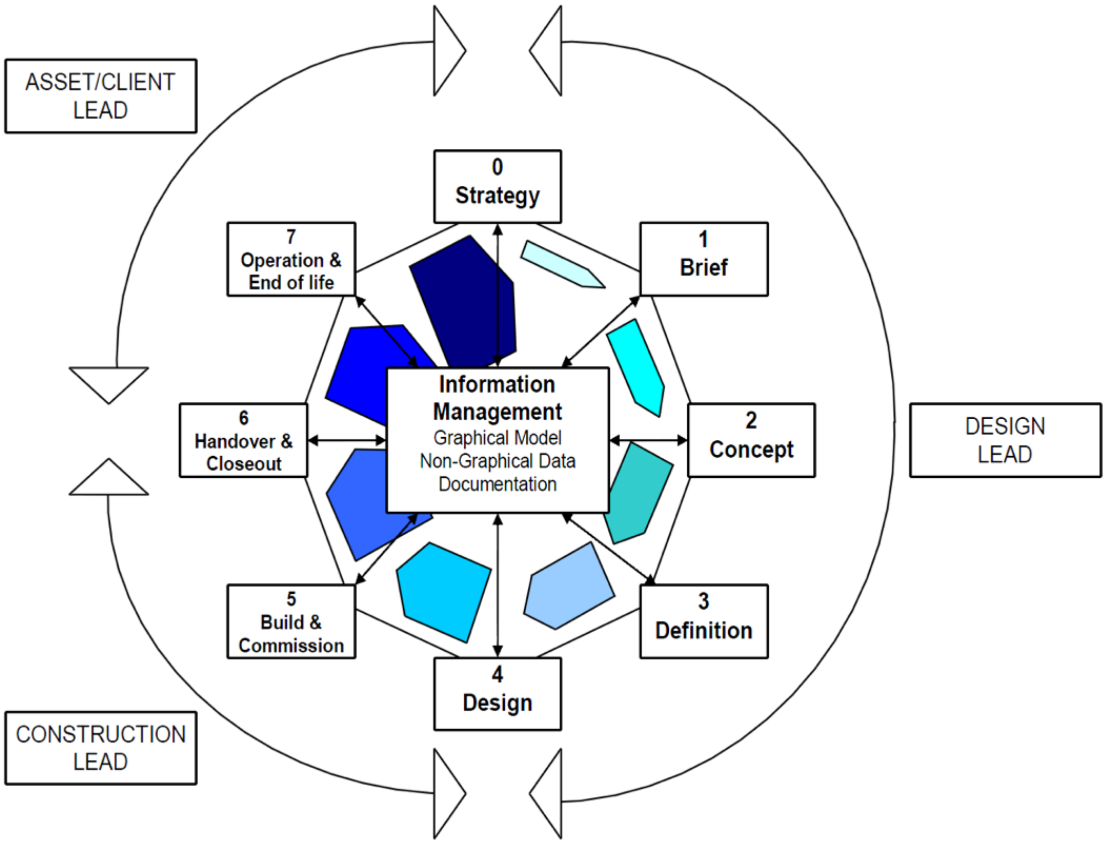


Figure 3. Construction Industry Council (CIC) BIM Cyclical Diagram, 2016.

The COTAC Report, 2016, compiled heritage principles with the CIC diagram and creates the COTAC HBIM Cyclical Diagram (Maxwell, 2016). It took five relevant heritage organisations, synthesise their principles, and merged them with the CIC diagrammatic framework. This five organisations where: the ICOMOS Education and Training Guidelines, the BS7918: 2013 Guide to conservation of historic buildings, the application of Historic England Conservation Principles Policies and Guidance of 2008, UNESCO Disaster Risks Management Cycle, and the previous COTAC diagram generated in 2014 (British Standards Institution, 2013).

The AEC (UK) BIM Technology Protocol (Architectural, Engineering and Construction (AEC) Initiative, 2015), launched in 2015, is aligned with the PAS 1192-2:2013 BS EN ISO 19650 (Sackey *et al.*, 2014) and provides BIM standards and specific guidance for diverse modelling software. In the Spanish context, The Building Smart Spanish Chapter developed the u-BIM guides in 2014 to help the implementation of BIM in different areas e.g. facilities management, design, energy consumption (Building Smart Spanish Chapter, 2014). This includes one section dedicated to existing buildings. Recently, the Building Smart Spanish Chapter has created the HBIM commission to adapt HBIM to the needs of Spanish heritage projects. The author of this thesis and Prof. Jorge García-Valldecabres, co-supervisor, are active members of this group. Nieto developed a method to record HBIM floors in 2016 taking into consideration the results obtained by Murphy Nieto (2016).

In the UK context, Historic England published “BIM for Heritage”, in 2017, to guide owners, end-users and professionals to develop Historic Building Information Models (Antonopoulou and Bryan, 2017). It defines what HBIM is, its benefits, how to manage BIM data, how to commission HBIM, and describes interesting cases where HBIM was used. It proposes a life cycle principle, Figure 4, with the distinct steps. One important contribution of this guide is the definition of LOD in HBIM, which was not addressed in previous protocols.

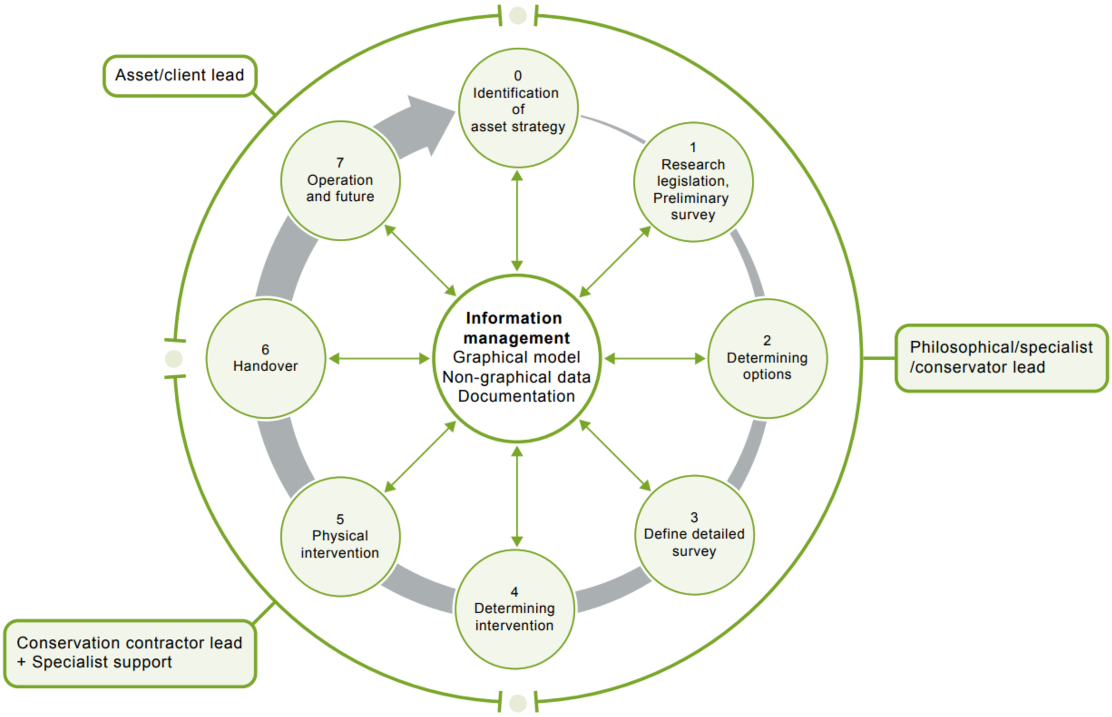


Figure 4.BIM for Heritage Life Cyclical Principle. Historical England *BIM for Heritage*, 2017.

There are guidelines available on heritage intervention practices. For instance, International Restoration Charters created different documents describing best good intervention practices and methods. Different heritage organisations such as Heritage England or the Instituto del Patrimonio Cultural de España (IPCE) had been updating their interventions guides, creating specific heritage guides for particular heritage types (i.e. industrial, religious, defensive) and proposing laws (a.e. Law of Spanish Legacy) (Spanish Ministry of Presidency and Territory, 25 de junio de 1985). Also, architects as Moreno-Navarro (Moreno-Navarro, 1988) designed their own heritage project methodologies, defining the steps of the intervention project as follows: (1) previous studies; (2) intervention objectives; (3) architectonic project; (4) construction; and (5) intervention diffusion.

The United Kingdom's Level 2 BIM Mandate and What it means for construction, launched in 2016, required public construction project stakeholders to be able to exchange project data through a common file format (Edwards, 2017).

BIM protocols have been developed to make construction processes more efficient. In terms of protocols which merge Restoration with BIM, Megahed (2015) developed an initial theoretical framework explaining the different aspects of historic preservation and management. A Metric Survey Specification was created defining the different steps of a heritage survey using different techniques, including HBIM (Bryan *et al.*, 2013). During a workshop held in Luxor, Egypt, Counsell and Nagy (2017) proposed a cloud-based workflow for analysing best practices to 3D point clouds.

2.6.1 DISCUSSION OF THE EXISTING PROTOCOLS

The existing HBIM protocols and guides present efforts to link conservation principles with BIM technologies. However, HBIM is still an emerging area and further research is needed in identifying specific stakeholder's needs, better aligning these with traditional heritage procedures, and evaluating these through practical implementations of HBIM. Historic buildings last centuries and the existing literature demonstrates the need for BIM based protocols to support the management of heritage buildings' interventions (Barazzetti *et al.*, 2015; Megahed, 2015).

HBIM involves multiple stakeholders that usually work in different geographic locations that makes collaboration challenging. Different authors stand that a possible solution will be the creation of a Common Data Environment (CDE) to synchronise the information in real time (Edwards, 2017). CDE is a central information repository that can be accessed by all stakeholders in a project. Whilst all the data within the CDE can be accessed freely, ownership is still retained by the originator. Cloud storage is a popular method of providing a CDE, although it could also be a project extranet. The scope and requirements for a CDE are defined in PAS 1192-2:2013 BS EN ISO 19650 (Sackey *et al.*, 2014).

2.6.1.1 Benefits

The existing HBIM protocols discussed above provide:

- Valuable HBIM definitions and its benefits
- Indications of how to manage BIM data
- Information about how to commission HBIM
- The stages of the HBIM life cycle
- The link between conservation principles and BIM technology

2.6.1.2 Drawbacks

The existing HBIM protocols discussed above require further development in terms of:

- The stakeholders who are involved in each step.
- The HBIM stakeholders' needs in each step.
- A better alignment between traditional procedures and BIM processes.
- Evaluation in practical implementations of HBIM.

These drawbacks justify the need for a new protocol, BIMlegacy protocol. These drawbacks would be addressed through the new protocol by defining the specific stakeholders involved in each step, the needs of the stakeholders in terms of technology, aligning the traditional procedures with HBIM, and applying the protocol in case studies. One example of aligning with traditional procedures is the representation of pathologies, which traditionally has been represented with hand drawings or laborious AutoCAD drawings, will be done with HBIM technology using 3D objects, filters, and associated external data in the model.

2.7 HBIM PLATFORMS

Collaboration platforms and visualisation tools are essential elements for HBIM stakeholders (Arayici *et al.*, 2017). CDE specifies a single source of information for the project used to collect, manage and disseminate project information through strictly controlled processes (Antonopoulou and Bryan, 2017). It is an informatics tool to allow a transparent and controllable process (Building Smart Spanish Chapter, 2014). CDE is the most optimised framework to allow interdisciplinary collaboration in BIM environments. A CDE could be a project server, an extranet or a cloud-based system (Camarinha-Matos *et al.*, 2017b). The success of the CDE depends on the BIM infrastructure, which means the software, hardware and networks. Also, a protocol of use must be in place and strictly adhered to by all members of the project team to ensure information consistency and quality (Antonopoulou and Bryan, 2017). The benefits of using CDE are the possibilities to work with people who are geographically separated, the immediacy of access to the information, to order and filter different layers of information, and to control the permits (Singh *et al.*, 2011).

BIM platforms started due to the necessity of interoperability and synchronisation. Grillo and Jardim-Goncalves, in 2009, predicted that the use of BIM as a central repository for the building project information could change information management for a project and throughout its life cycle. They proposed BIM e-platforms for the exchange of technical data and BIM models (Grilo and Jardim-Goncalves, 2010).

The digital platform DIF CAM (2017) allows the quick acquisition of digital data of the building and it can be used to automate monitoring processes of the building conditions. This kind of technology can be used for preservative conservation of built preservative, it allows the management systems and they provide a solution (González, 2017).

Online platforms among BIM are single source of information to collect, manage and disseminate graphical and non-graphical information (Standard I. S.O., 2010). Even the Spanish Ministry of Development encourages the development of big data in cloud systems with the principles of the National Plan of BIM implementation that this ministry promotes. The Spanish chapter of Building Smart stands that managing the information is one of the five pillars of BIM (Building Smart Spanish Chapter, 2014).

BIM Platforms hosted in the cloud are a common topic of study both between scientists and between BIM software companies (Camarinha-Matos *et al.*, 2017a). Latency and the real-time synchronisation of BIM data for collaborative decision-making is an important practical matter (Du *et al.*, 2018). Latency articulates the well-functioning of any platform and it should be taking into account when designing any kind of CDE. BIM platforms are emerging which are trying to meet the requirements of different architecture sectors. Results of BIM case studies where CDE where used as central repository have, in general, been very successful. The most relevant ones are detailed bellow:

Pergn et al. (2007) were pioneers investigators of CDE solutions designing a system to assist contractors in building core competencies as well as sustaining competitive advantages. They developed a dynamic decision support system to help refurbishment contractors. The results of this incipient study confirmed that hosting data in a cloud repository helped the decision making on site. Their work was used as a basis by San Martín et al. (2010), who developed a web application with an intuitive interface that contained 3D models with geometric information and non-geometric where users could access and consult it. This was a revealing use of 3D models even though the models were not created using BIM software (San Martín *et al.*, 2010). Organising HBIM information from multiple sources into platform-based integration is the most important challenge. This issue must be addressed up front in the contract documents (Afsari *et al.*, 2016).

In the construction sector, Grover and Froese experimented with a socio-platform where interdisciplinary stakeholders could collaborate. This investigation highlighted the importance of taking into consideration the social layer when collaborating with different stakeholders and not just the technical issues (Grover and Froese, 2016). This work supposed a contribution since it was the first socio-platform for architecture HBIM, which was further developed with Arthur's investigation. In the housing maintenance sector, Arthur (2017) designed a central controller that connects a variety of smart devices in the home such as door locks, cameras, lights, and thermostats. This platform is hosted in the cloud to enable collaboration and the linking of BIM models with other sources. Arthur's success was based on the fact that it was enabled for Big Data, has an Industry Foundation Classes (IFC) compliant BIM engine, and an Internet of Things (IoT) Hub for handling IoT data (Arthur *et al.*, 2017). The results of the project confirmed that contemplating collaboration holistically helps to improve the quality of the project.

Interactive databases emerged in the architecture sector, for example Baik and Boehm (2017) proposed to archive all HBIM models in an interactive database for scheduling and monitoring building maintenance and link them with fire prevention systems. Howell designed a CDE to control urban water solutions with a well-articulated platform based on a detailed water value chain ontology. This investigation stated that semantic interoperability solutions are essential and coincides with Arthur's idea; loT can integrate large data models with dynamic data streams. Thus, this platform supports more powerful applications for operational built environments (Howell *et al.*, 2017).

CDE applications are very useful to control construction budgets. Jeong investigated BIM-integrated construction operation simulation for just-in-time production management but without creating a formal CDE (Jeong *et al.*, 2016). Later, Lee developed a 3D BIM assisted productivity measurement method prototype for field work. The advanced construction productivity measurement method will allow workers to be more precise in their tasks and perform productivity tracking. The most relevant result is a productivity trend curve which is generated based upon the application of the prototype to a case study (Lee *et al.*, 2017).

Li developed an Internet of Things enabled BIM platform for prefabricated construction. This platform was used in a real case study with large storey buildings. They concluded that it improve the effectiveness of the team and improves the data collection on site (Li *et al.*, 2018). The success of this study encourages this investigation to include construction phase within the HBIM platform. Dave developed a platform that integrates the built environment data with

IoT sensors and their results show that both the end users and other research groups can benefit from such platforms by either consuming the data in their daily life or using the data for more advance research (Dave *et al.*, 2018).

BIM companies have launched their own online BIM platforms. Autodesk has BIM360Team that is a centralised workspace to view models and drawings in a web browser. Stakeholders can access the project information from different devices. Graphisoft has BIMcloud, which is a central resource management platform in the cloud. Allplan presented BIM+ as the cloud-based open BIM platform. All systems focus on new buildings from the design perspective, which do not fulfil the necessities of heritage projects (Afsari *et al.*, 2016).

The main difference between BIM and HBIM, in terms of CDE requirements, is that in heritage projects an extra layer of historic data needs to be managed. Recent studies concluded that the accessibility to historic information will improve the quality of the projects and facilitate decision making (Antonopoulou and Bryan, 2017). Thus, a common workspace is required to control and to order all different layers of historic and archaeological information. Historical England describes the principles that a CDE for heritage projects should have, Figure 5, which has been taken into account to develop BIMlegacy (Antonopoulou and Bryan, 2017).

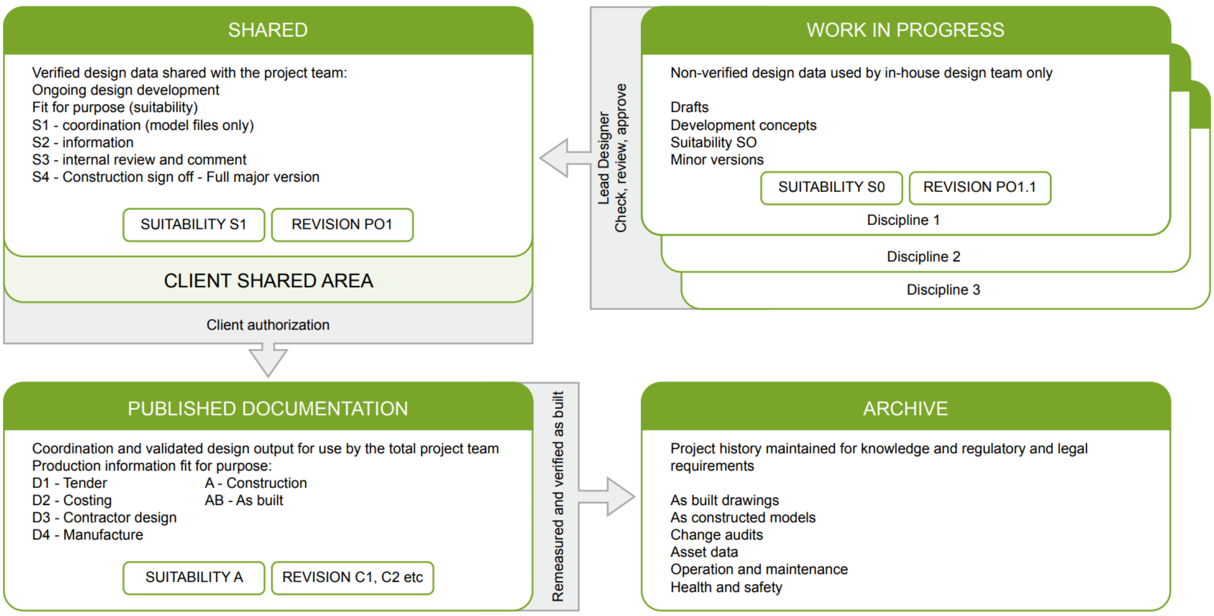


Figure 5. An outline of CDE principles. Historical England, 2017.

Canciani et al. (2014) have combined 3D models with a GIS data that allow the archiving, editing, sharing, and showing linked data. The model contains information of the current building, recent excavations, and hypothetical reconstruction of disappeared buildings. With this data, a multimedia guide for mobile applications records data of the database and shows them in real time (Canciani *et al.*, 2013).

Guidi and Russo (2015) presented the virtual reconstruction of Villa Giulia with Etruscan style, even representing the vegetation of that time. The scenes can be updated and reused for new projects. The archaeologist select the historic information that must be transmitted to the touristic public visits (Guidi and Russo, 2011).

Barazzeti (2016) developed a proceeding to update HBIM models in the cloud to have remote access to information between mobile devices. Data has been produced from the scanner laser and photogrammetry, as a result, an accurate 3D model, of a relatively small file on size, available and useful for all stakeholders (Barazzetti *et al.*, 2015).

Petro BIM is the most complete example of a platform in the heritage sector. It is an online tool where HBIM models can be uploaded and accessible for different stakeholders. It has a consulting nature and it cannot be considered as a real time workspace (PetroBIM, 2014). It focusses on the survey stage of the project and not the whole life cycle of the building, which would include the construction and maintenance. In the next section the different literature sources are compared and contrasted to the need and problem being investigated.

2.7.1 DISCUSSION OF THE EXISTING PLATFORMS

After performing the literature review, it is possible to conclude that there is not a CDE specialised in heritage projects management but internet tools to assist specific labours related with the heritage survey. Therefore, other architecture CDE have been studied, for example the ones explained in the previous section (Jeong *et al.*, 2016; Grover and Froese, 2016), even though they were not specifically designed for HBIM projects. The benefits and drawbacks of the studied platforms are pointed bellow:

2.7.1.1 Benefits

- HBIM models can been uploaded and accessible for different stakeholders
- HBIM models updated in websites can be very useful as consultation and touristic divulgation tool.
- Combined 3D models with a GIS data allow the archiving, editing, sharing, and showing linked data
- Small files on size were available in the cloud

2.7.1.2 Drawbacks

- There is not a specific platform where heritage stakeholder can unify in real time their information
- The existing platforms do not host the hole life cycle of the heritage buildings
- Not all stakeholders can access to the existing platforms
- The information in the existing platforms do not synchronise with the information in the HBIM models in real time

In conclusion, there is not a specific HBIM platform which unifies in real time heritage information and serves a workspace for the interdisciplinary stakeholders (Dore and Murphy, 2017). This documented scientific gap encourages the development of BIMlegacy platform as the CDE to put into practice the BIMlegacy protocol.

3 RESEARCH METHOD

The purpose of this study is to design a protocol to manage HBIM interventions in heritage buildings and to put it into practice using BIMlegacy platform in a real case study. In the previous sections, the research context and problem was defined, as well as the research gap of the literature review. In this section, the research approach carried out in this study is explained; to achieve this purpose, this section is organised in three sections: 3.1 explains the categories of sciences; 3.2 presents the Design Science Research (DSR) philosophical and methodological approach, and 3.3 explains the design of this investigation.

3.1 CATEGORIES OF SCIENCES

Van Aken (2004) suggests that there are three categories of sciences: (1) the formal sciences, such as philosophy and mathematics; (2) the explanatory sciences, natural and social sciences; and (3) the design sciences, such as engineering, medicine, and modern psychotherapy.

"Formal sciences are empirically void" (van Aken, 2004), whereas explanatory science aims to describe, explain, and possibly predict observable phenomena. Their mission is to build system of propositions whose main test is their internal logical consistency. They are based on two activities: discovering, proposing scientific affirmations; and justification, proving and validating the discovering according to the book "The Structure of Discovery" (Caws, 1969). Design science try to improve productivity by focusing on utility; in contrast, natural sciences focus on searching the truth (Kuechler *et al.*, 2007).

Design science is also named artificial sciences to distinguish them from natural sciences. In his book, "The Sciences of the Artificial" (Simon, 1969), he distinguishes between "natural science" and "artificial science" also known as "design science". Simon (1969) considers the fact that engineering, medicine, business, architecture and painting are concerned with how things should be and not how they are. Holmström (2009) also affirms that architecture and engineering belong to design science (Holmström *et al.*, 2009). This research is framed in the design science since heritage architecture is the object of study. Specifically, BIM is a technological branch of the construction sector, which affirms more the belonging of this study to the design science.

3.2 DESIGN SCIENCE RESEARCH

3.2.1 DESIGN SCIENCE RESEARCH PHILOSOPHICAL APPROACH

This research adopts design science approach, which is a "lens" or set of synthetic and analytical techniques and perspectives (complementing positivist, interpretive, and critical perspectives) for performing research in Information Systems (IS) (Hevner and Chatterjee,

2010) (van Aken, 2004). Annexe 1 presents different philosophical approaches studied to have a basis to better chose design science research.

Design science focus on the solution and its main result is a technological rule. The management theory is the result of the prescriptive research, which has helped to “tested and grounded technological rules” (van Aken 2004). Drawing from the economics of knowledge field, useful Design Science knowledge can be divided into two distinct types: descriptive knowledge (denoted Ω or omega) is the “what” knowledge about natural phenomena and the laws and regularities among phenomena; whereas prescriptive knowledge (denoted Λ or lambda) is the “how” knowledge of human-built artefacts (Mokyr 2002). Figure 6 shows that both Ω knowledge and Λ knowledge comprise a comprehensive knowledge base for a particular DSR domain.

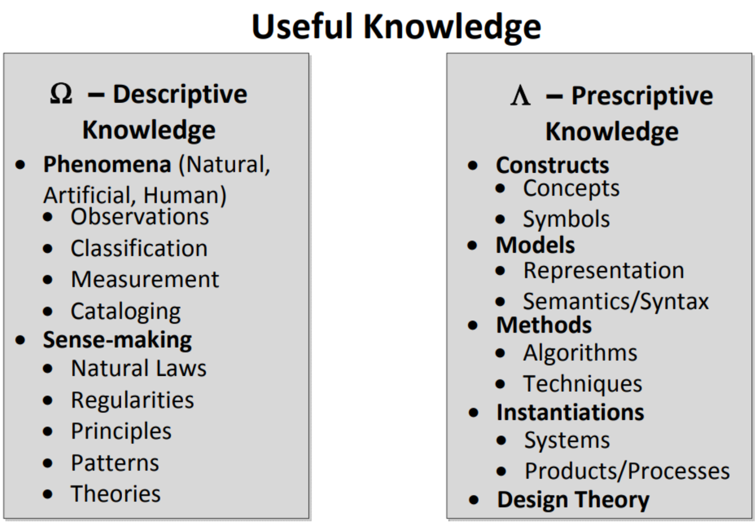


Figure 6. The Design Science Research Knowledge Base. Positioning Design Science Research for Maximum Impact (Gregor and Hevner, 2013).

From the Ω base, the researcher draws appropriately relevant descriptive and propositional knowledge that informs the research questions. Relevant knowledge may be drawn from many different elements in Ω, including existing justificatory theories that relate to the goals of the research. At the same time, from the Λ base, the researcher investigates known artefacts and design theories that have been used to solve the same or similar research problems in the past. The objective is to provide a baseline of knowledge on which to evaluate the novelty of new artefacts and knowledge resulting from the research. In many cases, the innovative design research contribution is an important extension of an existing artefact or the application of an existing artefact in a new application domain. The success of a design research project is predicated on the research skills of the team in appropriately drawing knowledge from both Ω and Λ bases to ground and position the research; the teams’ cognitive skills (e.g., creativity and reasoning) in designing innovative solutions; and the teams’ social skills in bringing together all the individual members’ collective intelligence via effective teamwork (Mokyr 2002).

There is much debate around the need to adopt a particular philosophical view point, with much of the debate “around positivist and interpretivist research philosophy or between quantitative methods and qualitative methods” (Saunders and Lewis 2012, p.129). However, in recent times it has been suggested that consideration is given to the philosophy adopted as a multi-dimensional set of continua rather than as distinct positions. As is showed in section 3.3, knowledge in this research has been achieved in an inductive process because it emerges from the reality studied.

In conclusion, the philosophical position of this research is the artificial science or design science but also takes ontological constructivism, as the realities of the discussed phenomenon are created with the interactions and perceptions of the people involved in the investigation, combined with interpretivist but including theory verification from epistemological positivism. In general, this research could be considered exploratory because there are not specific previous studies in heritage management protocols and platforms.

3.2.2 DESIGN SCIENCE RESEARCH METHODOLOGICAL APPROACH

This section explains the methodological and practical approach of design science unlike the previous section that explained the philosophical approach. Design Science Research (DSR) focuses on solving practical problems with theoretical relevance, providing theoretical contributions within the solution and producing artefacts as an output (Holmström *et al.*, 2009). DSR needs to take into account: (1) to find practical applications to common design problems, its application should lead to the intended results (van Aken, 2004) and (2) the optimization methods developed in statistical decision theory which is supported in computational tools (Simon, 2006).

DSR has been an important paradigm of Information Systems (IS) research since the inception of the field, and its general acceptance as a legitimate approach to IS research is increasing (Hevner and Chatterjee, 2010; Kuechler and Vaishnavi, 2008). DSR has been practiced for some time in the engineering and IS disciplines, although under a variety of labels. Simon (1969) provided the seminal work on the “sciences of the artificial.” Relevant work in information systems has been referred to as “systemeering”, this specific term was stablished by Ivari (1983), a “constructive” approach, and “systems development” or an “engineering approach” . Yet mainstream recognition of DSR in information systems is acknowledged to have occurred with the 2004 through Hevner et al. publication in MIS Quarterly (Kuechler and Vaishnavi, 2008).

DSR develops knowledge to create artefacts that improve processes (van Aken, 2004). This means that, DSR tries to create something that does not exist in nature (Kuechler and Vaishnavi, 2008). The aim of design science is (van Aken, 2004) page 226:

> “to develop scientific knowledge to support the design of interventions or artefacts by professionals and to emphasise its knowledge orientation: a design-science is not concerned with action itself, but with knowledge to be used in designing solutions, to be followed by design-based action.”

Simon (2006) stands that DSR is concerned with the devising and evaluation of man-made artefacts aiming to resolve real-world problems. An artefact is created to resolve a practical problem, but this artefact needs to be empirically evaluated. Thus, there is a notable pragmatic interest because it is not sufficient to describe and understand a problem: it is also necessary to actually develop and test solutions (Holmström *et al.*, 2009). On the contrary, other methodology approaches such as action research focuses in the processes to resolve problems, but there is not a requirement for demand to resolve these issues (Holmström *et al.*, 2009).

At the beginning of a design science research effort, a means-ends analysis should be devised to represent the present state, the desired state, and the difference between those two. A proper presentation of the problem is fundamental, meaning that it should be understandable by all stakeholders. If problems are related with physical objects, the solutions can be represented as plans, 3D models or engineering drawings. Problems related with actions can be represented with flowcharts and software solutions (Simon, 2006). March and Smith (1995) suggests that there are two fundamental activities in design science research: building a solution and evaluating the solution. The same authors explain that building is the process of constructing an artefact for a specific purpose, and evaluation is the process of determining how well the artefact performs in fulfilling its purpose.

Holmstrom and Ketokivi (2009) explain that along with the development and testing of the solution, the theoretical relevance of the solution design must be established. Humans solve problems by trial and error and selectivity, which means in an artificial manner and improve them over time by designing better artefacts. The participants should be treated as change agents trying to manage the system to achieve their own objectives in a changing environment (Simon, 2006). The true efficiency of the system resides in the holistic perspective, understanding holism as the theory that parts of a whole are in intimate interconnection. Following these principles, many complex processes have been created in computer software since they can achieve complex objectives and learn from previous fails. It is an iterative process of testing and improving (Simon, 2006). Another loop can also occur at the conclusion stage, feeding back into the problem awareness stage and creating a new research cycle. According to Hevner et al. (2004), the construction process is inherently iterative and incremental: the evaluation stage provides essential feedback for the construction phase in terms of the quality of the development process and the solution itself.

The design science approach assist in resolving the application and relevance problems that happens in Architecture disciplines such as Heritage Architecture. As it was framed in section 2.2, heritage architecture focuses on resolve historic buildings preservation problems to transmit heritage legacy to future generations. BIM is altering heritage architecture field and their stakeholders are trying to achieve their tasks in an unfamiliar environment, which can be perceived as a threat. According to Simon criteria, the implementation of BIM in the heritage architecture should be holistically studied (Simon, 2006).

Prescriptive knowledge concerns artefacts designed by humans to improve the natural world. Design theories are also prescriptive knowledge, so the Λ knowledge base includes artefacts. March and Smith (1995), in a widely cited paper, contrast design science research with natural science research and propose four general outputs for DSR: constructs, models, methods, and instantiations (March and Smith, 1995). Simon (1996) labels such knowledge as belonging to the sciences of the artificial.

A **design theory**, which is an abstract, coherent body of prescriptive knowledge that describes the principles of form and function, methods, and justificatory theory that are used to develop an artefact or accomplish some outcome (Gregor and Hevner, 2013). Design theory can include the other forms of design knowledge: constructs, models, methods, and instantiations that convey knowledge (Gregor and Hevner, 2013).

Thus, it is established that design science knowledge is manifested in the form of artefacts—constructs, models, frameworks, architectures, design principles, methods, and/or instantiations—and design theories (Gregor and Jones, 2007). Instantiation is generally referred to as a material artefact while the other types of artefacts are referred to as abstract artefacts. A design theory usually includes abstract artefacts and can also include instantiations.

Constructs provide the vocabulary and symbols used to define and understand problems and solutions; for example, the constructs of “entities” and “relationships” in the field of information modelling (Gregor and Jones, 2007). The correct constructs have a significant impact on the way in which tasks and problems are conceived, and they enable the construction of models for the problem and solution domains.

Models are designed representations of the problem and workable solutions. For example, mathematical models, diagrammatical models, and logic models are widely used in the IS field and new and more useful models are continually being developed. Models correspond to “principles of form” in the Gregor and Jones (2007) taxonomy: the abstract blueprint of an artefact’s architecture, which show an artefact’s components and how they interact (Gregor and Jones, 2007).

Methods are algorithms, practices, and recipes for performing a task. Methods provide the instructions for performing goal-driven activities. They are also known as techniques (Mokyr, 2002) and correspond to “principles of function” in the Gregor and Jones taxonomy and Bunge’s (1998) technological rules (Gregor and Hevner, 2013).

Implementations or instantiations are the physical realisations that act on the natural world, such as an information system that stores, retrieves, and analyses customer relationship data. Instantiations can embody design knowledge, possibly in the absence of more explicit description. The structural form and functions embodied in an artefact can be inferred to some degree by observing the artefact.

Technological rules can also be considered a sixth type of output. According to Van Aken (2004), technological rules are chunks of general knowledge involving a broad prescription for addressing a class of problems in an intended context of application. It is implicit in March and Smith (1995) that constructive research initiatives should provide all the four outputs. In conclusion, the research design adopted in this investigation (explained in section 3.3) has been non-experimental since it has been observed in its real environment (heritage work teams). The open research design adopted has been modified during the research and gave as a result the protocol, which is considered a "model" according to the classification, and a web platform, which is considered an "instanton" because is a physical realisation.

3.2.3 REASONS WHY DESIGN SCIENCE RESEARCH WAS CHOSEN AS RESEARCH METHOD

Design Science Research (DSR from now on) was considered the most appropriate approach to undertake the research because:

(1) Even though the research problem is practical, it also has theoretical relevance. The research problem is to improve the efficiency of heritage projects workflow, and the theoretical relevance resides on the description of the efficiency of heritage projects and the usefulness of HBIM.
(2) Artefacts were developed as an output. A protocol to manage heritage buildings and a web platform for HBIM projects are the artefacts developed as outputs. The design science approach is concerned with the devising and evaluation of man-made artefacts aiming to resolve real-world problems (March and Smith, 1995).

Both reasons are linked to the main aims of DSR as a methodological approach. There is a large tradition in engineering and architecture of using design science to solve problems related with practice and technological issues (Niiniluoto, 1993; Anshelevich *et al.*, 2003; Holmström *et al.*, 2009). Numerous studies have been developed through design science research in the construction and architecture sector (Chaves et al., 2015) (AlSehaimi *et al.*, 2012) (Holmström *et al.*, 2009).

Design science investigations develop novel solutions for existing problems adapting existing tools or using these tools in a novel manner (Gregor and Jones, 2007).

3.3 RESEARCH DESIGN

The research design adopted (see Figure 7) was divided into five stages following the principles of DSR: identify the problem, define objectives, design the solution, implement the solution and evaluate the solution (Peffers *et al.*, 2007). These stages were applied to the three phases of the investigation; these three iterative phases adopted a multilevel sequential mixed design as it seeks to gain knowledge from the different evaluations and to continue improving the artefact (see Figure 7). Thus, each of these three phases, in turn, followed the five stages. Figure 7 represents the structure of the phases and the stages, it is just the skeleton, and the full figure of the research design is Figure 8, which is in the next page.

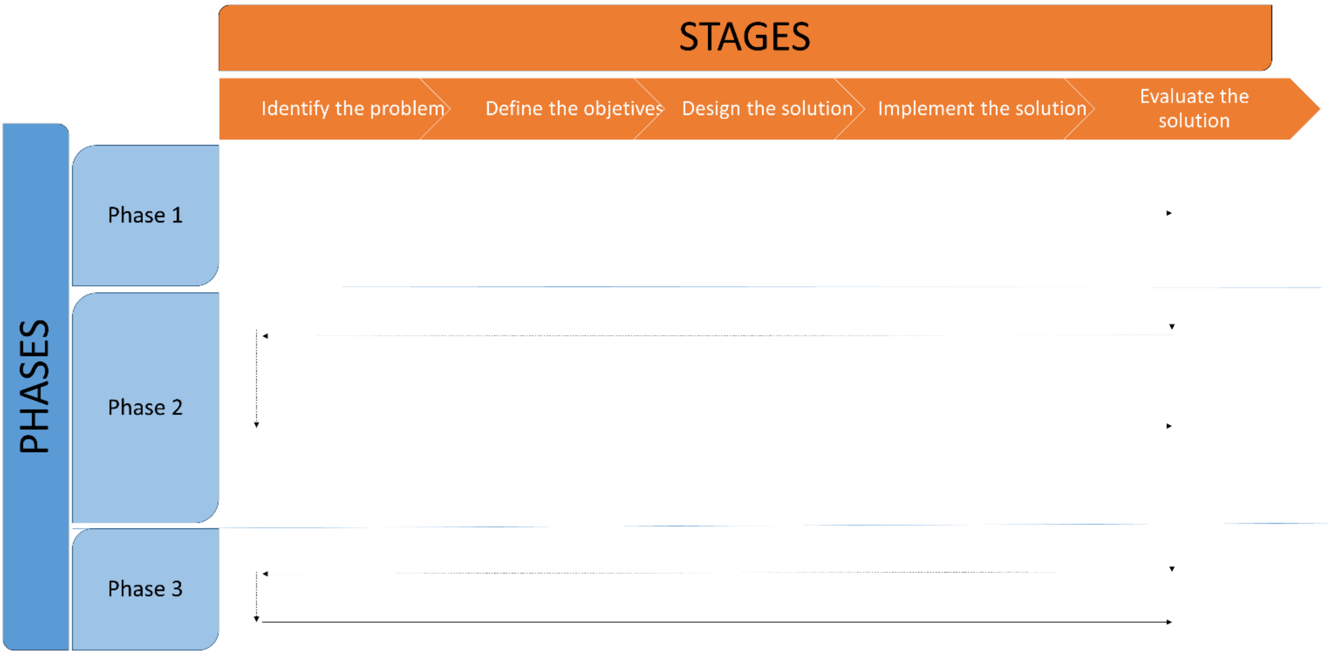


Figure 7. Stages and phases of the research design, 2015.

The two designed artefacts, named BIMlegacy protocol and BIMlegacy platform (the technological tool), were designed and evaluated in different cycles in two heritage projects: (1) Fixby Hall Gregorian building, (2) San Juan del Hospital, a gothic ecclesiastic complex in Valencia, focusing in the BIM modelling. Those projects were chosen as case studies because of their heritage richness, complex geometries, and the researchers' access to the involved stakeholders. In phase 2 and 3, the technical artefact that is BIMlegacy platform, was also designed and evaluated within San Juan case study. The three research phases are described as follows, Figure 8.

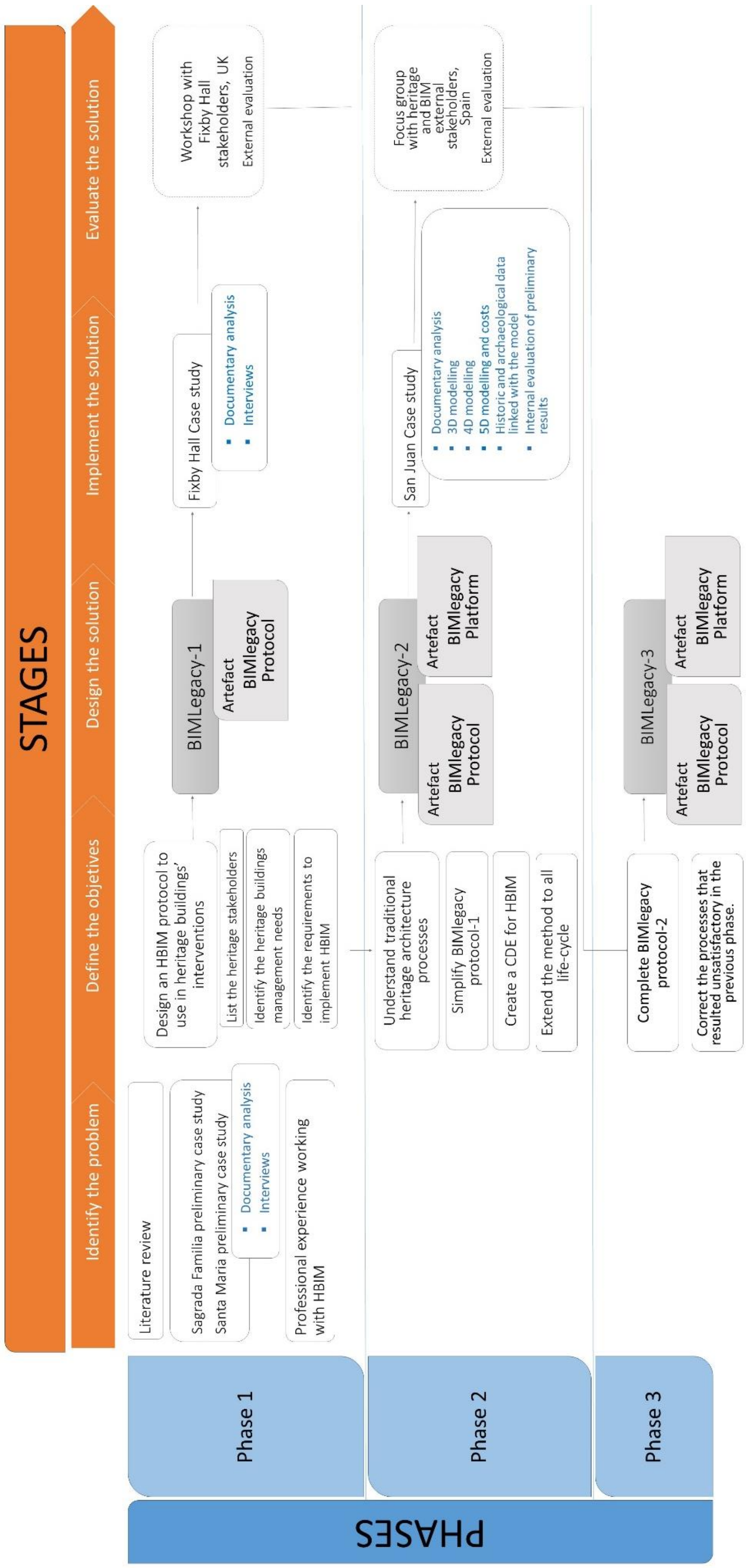


Figure 8. Research design, 2017.

3.3.1 PHASE 1

The research problem was identified through the literature review, the analysis of two preliminary case studies, and the analysis of the personal experience working with HBIM. The study was conducted through a systematic literature review method and its subsequent analysis (Osterweil, 2006). The research design was divided into five steps: (1) preliminary approach and initial tests; (2) literature search; (3) classification of papers considering quantitative and qualitative analysis; (4) exploitation and analysis of results; and (5) summary of main contributions and in-depth study of the most relevant papers. These steps are explained henceforth. Thus, quantitative research strategy has been used in this stage mainly to cover a range of samples related with the study of the literature review where HBIM was used. Annexe 1 presents different research strategies studied to choose the right approach for this thesis. The analysis of the literature review assisted to obtain the requirements to implement HBIM.

Step 1 of the literature review allows familiarisation with the main concepts related to BIM, identifying keywords and designing search strategies. Familiarization with the main concepts consists of looking for and reading BIM manuals and Historic Architecture books. The research group attended International BIM congresses, such as EUBIM 2014 and 2015, worked in BIM architecture studios, and went to Revit User Group of Valencia (GURV) meetings. This initial rapprochement made it possible to identify a list of keywords.

Step 2 defines search strategies to find the greatest amount of papers available, as show in Figure 1. The central circle contains the words utilised in all search strategies such as "BIM", "BIM Management", and "3D Architectural Models". The lower right circle contains keywords related with HBIM; whereas the lower left circle has keywords related with laser scanning.

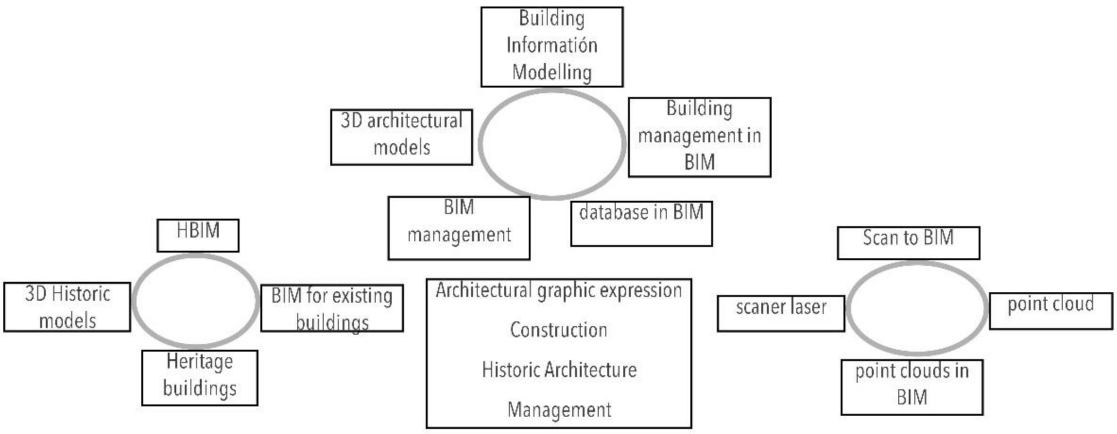


Figure 9. Keywords used in search strategies, 2014.

These **search strategies** were used to look for papers in: scientific search engines as Dialnet, Riunet or Science Research; scientific catalogues such as OCLC libraries and CrossRef search; **databases** as Inspec and Web of Science; and international journals such as Automation in Construction, Computers in Industry, Procedia Engineering, Engineering and Design Management, Journal of Construction Engineering and Management, Journal of

Management in Engineering, International Journal of Heritage in the Digital Era, Virtual Archaeology Review, and Revista Arqueológica de la Arquitectura; all of them are related to construction engineering or heritage topics.

Step 3 included quantitative and qualitative analysis of the resulting papers. All of them were analysed, several descriptive words were identified, and each paper was defined by a list of descriptive words. Subsequently these descriptive words were gathered considering the focus each referred to. Some items were discarded according to the following criteria: novelty (meaning papers published after the year 2012), closeness to the ancient architecture field, and method used.

In the quantitative analysis a total of 65 documents were initially found, but after the first filtering process there were 38 papers remaining. 11 duplicated papers were subsequently eliminated. As the papers were classified according to their relevance to the topic, 7 papers with a very low relevance were also removed. 20 papers remained following the filtering process. The fifth strategy was the most useful, as revealed in Figure 10.

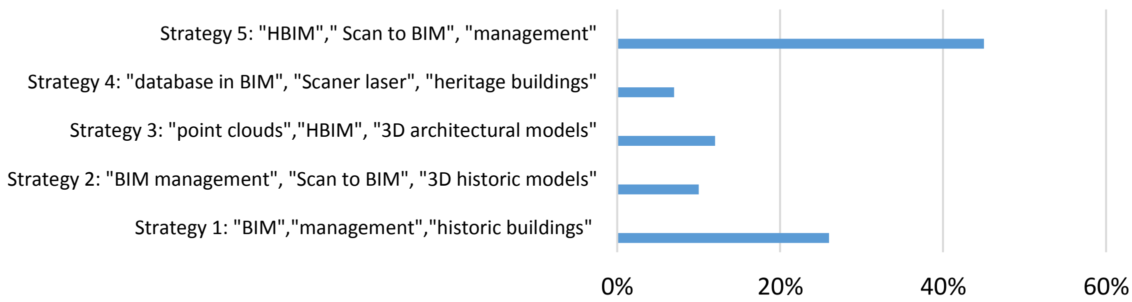


Figure 10. References found per search strategy, 2014.

The five research strategies used these keywords: (1) BIM, management, historic buildings; (2) BIM management, Scan to BIM, 3D historic models; (3) point clouds, HBIM, 3D architectural models; (4) database BIM, scanner laser, heritage buildings; and (5) HBIM, Scan to BIM, management. This last one was the strategy that achieved better results with more than the 40% of the founded papers. The qualitative results of this literature review were explained in the sections 2.3, 2.4, and 2.5. Some of these results were presented in the Construction Research Congress in Puerto Rico (García-Valldecabres *et al.*).

In step 4 the papers related to each descriptive word and therefore with each approach, were presented in charts. The charts were analysed and compared allowing the identification of the most important topics and items were grouped into differentiated themes. It was decided to create five fields of work using the affinity diagram technique (Carnevalli and Miguel, 2008): HBIM, Scan to BIM, BIM Management, TIC to BIM, and Social Factor in BIM.

The last step of the research design was a summary of the main contributions and an in-depth study of the most relevant articles. The previous reading and identification of descriptive words enabled the identification of the main contribution of each paper. In addition, the papers were classified by importance, taking into account the number of times the paper was quoted, the journal in which it was published, and the judgment of the research team. Conclusions about the state of the scientific development of each block were drawn to address the focus of the research.

The research problem was further identified with two preliminary case studies the Sagrada Familia Temple and Santa María of Vitoria Cathedral (Faulí Oller, 2008) that included an analysis of the heritage stakeholders and processes through document analysis (e.g. design drawings, technological implementation plans, databases) as well as ten semi-structured interviews with relevant heritage professionals who belong to those two relevant monuments. The interviewed stakeholders in both monuments included: (a) an architect of Sagrada Familia (13 years of experience), (b) a construction manager of Sagrada Familia (8 years), a technical architect (18 years), an archivist of Sagrada Familia (25 years), a topographical surveyor of Santa María (22 years), and a heritage diffusion expert of Santa María (12 years). Those stakeholders were selected because they could contribute with information that was not found in the literature (a.e. details of the construction works, data management system of the monuments). The questions asked included: What departments are involved in managing your monument? Which stakeholders are involved? How do you archive the produced information? The results obtained included a list of heritage stakeholders and heritage management needs to take into consideration when implementing HBIM. The results of this phase are placed in section 4.1.1.

The personal professional experience of the PhD candidate working with BIM was also used to identify the requirements to implement HBIM. The BIM professional experience comes from working as BIM manager during the last 6 years in two different companies Emma Architecten in Amsterdam (design architecture studio) and Vic Group in Valencia (construction company specialised in refurbishments of heritage apartments buildings with HBIM technology). This fact allows having an extended experience with HBIM professional practice since they were previously working on s and that used BIM.

The objectives of the phase 1 of the investigation were defined after identifying the problem. The objectives were to identify the heritage stakeholders, the heritage buildings management needs, and the requirements to implement HBIM.

The basis to design BIMlegacy protocol-1 were the results of the literature review, heritage specialists' interviews, document analysis, and the personal professional experience working with BIM. The techniques used to build BIMlegacy-protocol-1 were qualitative analysis of data with Nvivo scientific tool, affinity diagrams, and tree structures in a hierarchical form.

Nvivo is a qualitative tool that stores, organises, and retrieves data and rigorously back up findings with evidence (Robins and Eisen, 2017). It imports data from virtually any source – text, audio, video, emails, images, spreadsheets, online surveys, social and web content and more. With advanced data management based in statistical and affinity criteria, query and visualisation tools, NVivo organises data and creates groups, objectives and proposals. Nvivo codes statements and looks for similarities and affinities between different transcript data to order ideas that have been repeated in different interviews or founded in the documentary analysis (Robins and Eisen, 2017). The process carried out with Nvivo involved the following steps: (a) storing and sorting the transcriptions of the interviews; (b) categorising and analysing the sentiment, themes, and attributes of the statements (see Figure 11) −the software performs a statistical analysis to organise themes and statements from different transcriptions−; and (c) visualising and discovering with the tabulate tool of the software, which allows the visualisation of the results, to map ideas and explore connections between project items. From this analysis, a series of objectives and proposals for the improvement of the workflow in heritage projects were obtained and represented in three tables that are presented in section 4.1. of this document.

Figure 11. Nvivo coding system, each colour represents an idea or statement, 2015.

The proposals obtained with Nvivo were organised in an affinity diagram, which is a method developed to organise data by affinity, and is also known as the KJ method of grouping (Carnevalli and Miguel, 2008). Then, the groups of this affinity diagrams were organised in a systematic diagram (also known as the tree diagram), which organises data in tree form and this is used to detail the tasks and paths used to reach objectives (Curedale, 2016). Thus, the ideas were organised overlapping flowcharts, for example relating The Sagrada Familia processes flowchart, obtained from the document analysis and previously synthesised in a table, with literature HBIM concepts. Some of the HBIM concepts included were for example building record using laser scanning, the representation of constructive phases, the collaboration different stakeholders, and the creation of tender documentation from the HBIM model. BIMlegacy protocol-1 was the result of this process (see Figure 31) explained in detail in section 4.1.5.

This first version of the artefact was applied to Fixby Hall case study. This historical building was chosen because it is a medium sized private building, the owner is interested in applying HBIM, and it is accessible for the research team. The aim of the case study was to obtain further information about traditional work processes (in a context outside Spain) and to make the protocol more user-friendly. This historic listed building is in Huddersfield, UK, and it is used as golf club headquarters.

Building data was collected consisting of a general comprehension of the building, identification of the stakeholders and companies involved, a site visit, a photographic report, and analysis of old architectural designs of the building. This phase also involved the identification of relevant historic and architectural documents, the research of diverse stakeholders' archives, and the study of the 125-anniversary book of Huddersfield Golf Club (Smith, 2016).

Seven one-hour semi-structured interviews were developed with: (a) the property, a real state charter surveyor (26 years of experience), (b) the monument manager (8 years), (c) the maintenance manager (28 years), (d) the archivist (12 years), (e) the heritage outreach manager (9 years), (f) the interior architect (7 years) and (g) the contractor (12 years), who were involved in previous refurbishment projects in Fixby Hall. Questions included: "In the case that a refurbishment of Fixby Hall was needed, what type of procurement is likely to be adopted?", "what would your involvement be?" The questions aimed to identify any possible stakeholder that had not been considered, verify that all traditional processes were included, and identify possible issues related with HBIM implementation in the protocol. This case study assisted in improving the protocol by identifying further stakeholders, not discussed in the literature and linking traditional processes with HBIM processes.

In the evaluation stage, the BIMlegacy protocol-1 was presented at an interdisciplinary workshop with the main stakeholders involved with Fixby Hall. This one-hour and a half workshop included the owner of the building who is also a chartered surveyor (26 years of experience), the HGC director (8 years), the architect specialised in BIM (20 years), the planning consultant specialised in heritage (22 years) and the BIM consultant (3 years). These stakeholders evaluated the stages and activities of BIMlegacy protocol and proposed possible improvements. The main findings from this focus group were that BIMlegacy-1 needed to improve the historical documentation process linked with the HBIM models through a CDE where heritage stakeholders could work together, which in the end fostered to develop the second artefact: the BIMlegacy platform.

3.3.2 PHASE 2

Data analysis from phase 1, the results from the application of BIMLegacy protocol -1 in Fixby Hall, and the recommendations from the workshop supported the definition and refinement of **the objectives** to design BIMlegacy -2. The objectives of phase 2 were to understand traditional heritage architecture processes, to simplify BIMlegacy protocol-1, to create a CDE for BIMlegacy, and to extend the method to the entire life-cycle.

In phase 2, two artefacts were developed: (1) the protocol was refined and improved taken into consideration the knowledge achieved in phase 1; (2) the platform, which is the technological artefact created to apply the protocol in practice developed within the HAR2013-41614-R project entitled "Design of a Database, Management Model for the Information and Knowledge of Architectural Heritage"

BIMlegacy protocol-2, has been designed using techniques as the analysis of the workshop transcription with qualitative analysis of data with Nvivo scientific tool for scientific research, and building affinity diagrams, and tree structures in a hierarchical form (Robins and

Eisen, 2017). Some of the diagrams used to improve BIMlegacy protocol-2 were the Construction Industry Council (CIC) BIM Cyclical Diagram (Construction Industry Council-CIC, 2013)as was suggested in the validation of phase 1, and different guides provided by recognised Heritage organisations that had studied HBIM such as the International Council on Monuments and Sites (ICOMOS), Historical England, and the Council on Training in Architectural Conservation (COTAC).

BIMlegacy platform was required to develop work in practice, which entailed the **design of the technological artefact**. It is a Common Data Environment (CDE) where heritage stakeholders work in real-time and share information. The objectives were to investigate the functional requirements, the interface requirements, and the database requirements to design BIMlegacy prototype. It was designed in the frame of the project HAR2013-41614-R "Design of a Database, Management Model for the Information and Knowledge of Architectural Heritage" subsidised by the Spanish Ministry of Economy and Competitiveness, where two teams contributed:

(a) The heritage team, working on the list of heritage stakeholders' necessities, functional requirements, and to make the platform useful to future users, as well as on the user interface design. This team was coordinated by the author of this research and comprised of members of a multidisciplinary research group belonging to the Instituto de Restauración del Patrimonio (Universitat Politècnica of València): two heritage architects, one BIM manager, one BIM modeller, one engineer, a technical architect, an archaeologist, an historian, and a monument manager. This team was involved with this project three years in total, but not all members were exclusively working in this project.

The specific contribution of the PhD candidate within the designing BIMlegacy platform was as 3 years involvement in the project as BIM manager, performing the following specific tasks:

- The idea of design the platform online, as a CDE.
- The BIM professional practice (previously working on design architecture studios and construction companies that used BIM). Thus, this experience was also used to understand the HBIM necessities and improve the platform design.
- The designing of the BIM parameters.
- Coordination the design of the connection between the BIM model and the website.
- The coordination and leading of the BIM models.

(b) The supporting IT team, involved in the database requirements, interface requirements, software solution, and plug-in connection. This team was composed of two computer engineers and a management information engineer. Project HAR2013-41614-R "Design of a Database, Management Model for the Information and Knowledge of Architectural Heritage" lasted three years where the heritage team was intensely involved, with some of their members exclusively dedicated to this project. The IT team was involved with the project one year and for four of those months three members were exclusively dedicated to this project. Both teams had weekly meetings to contrast and check the developed work and in the programming works, one member of the heritage team and one member of the IT team were physically working in the same office to accurately perform the user testing. The design process of BIMlegacy involved the following tasks:

- Defining the functional requirements of the platform through the analysis of the stakeholders' interviews and the HBIM researchers' own experience.
- Analysing current heritage databases to understand the basis of heritage documentation (Howell *et al.*, 2017).
- Defining the workflow in BIMlegacy. Flowcharts were developed to order and connect the functioning of the platform, as displayed in Figure 12.

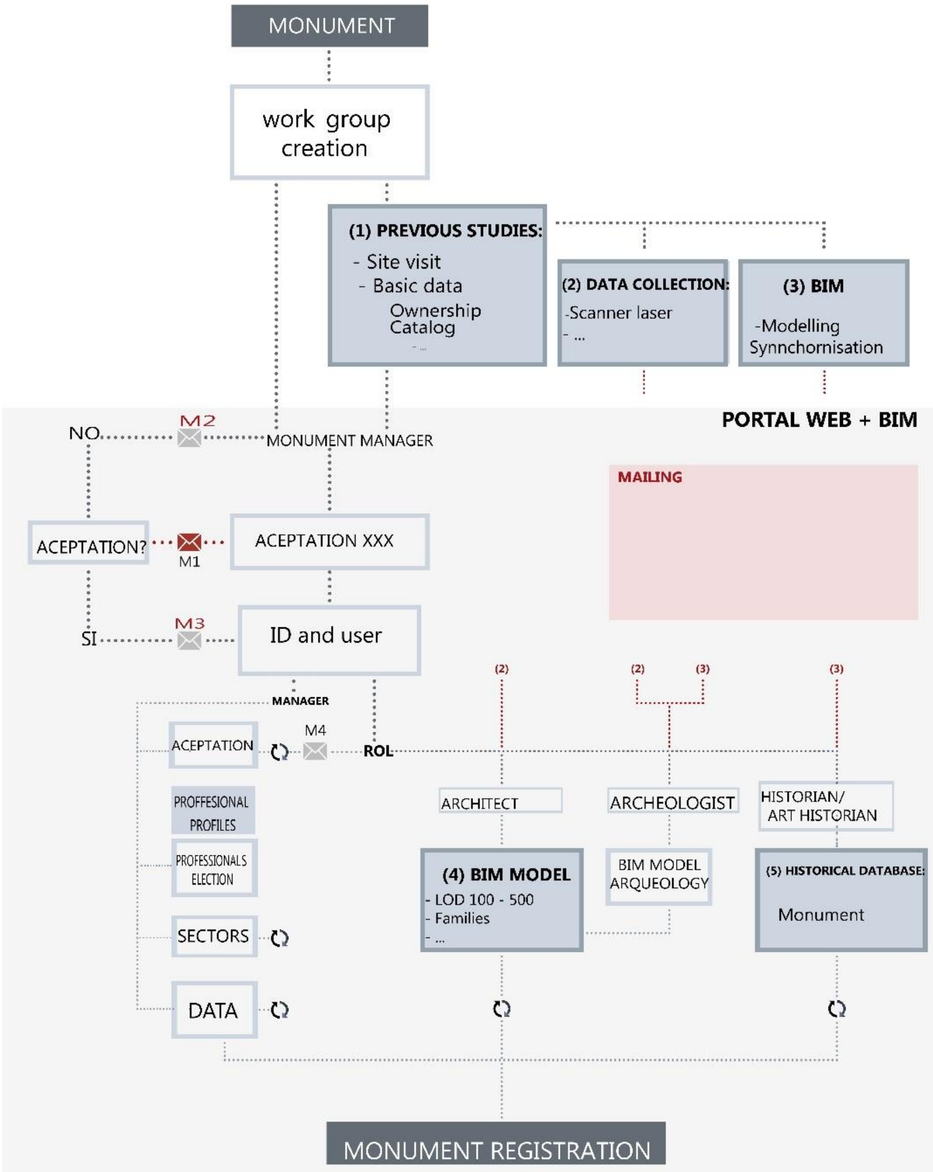


Figure 12. Workflow in BIMlegacy platform, 2016.

- Agreeing the database categories, as a result of the previous analysis of other heritage databases.
- Designing the interface and corporate image of the BIMlegacy platform. It was designed considering heritage values using colours and forms resembling ancient buildings and the technology.

- Definition of the distinct roles of the workspace and their permissions.
- Designing HBIM templates for medium private heritage buildings to upload in BIMlegacy website to help future users to develop their projects: BIMlegacy BIM Execution Plan (BEP), BIMlegacy Revit software of Autodesk templates, and HBIM families.
- Establishing the HBIM modelling requirements to use the platform. BIM modelling requirements were defined after analysing the HBIM literature, HBIM guides (Building Smart Spanish Chapter, 2014; Maxwell, 2014), published HBIM case studies (Grover and Froese, 2016; Ilter and Ergen, 2015; Eppich and Chabbi, 2007) and HBIM projects where the team members were previously involved in their own professional practice.
- Programming the platform. The goal was mapping the identification database of the Revit intrinsic database with the BIMlegacy online platform requirements of the IT solution were settled, and the programming work started (Quattrini *et al.*, 2015). The IT team and the heritage team collaborated intensively when programming the platform. A total of ten versions of the prototype were developed, each of them an improvement of the previous one. A series of tests and checks were achieved with the use of the plug-in, server, and website.
- Hosting the platform in a Wide Area Network (WAN) to make it accessible from different geographic locations. This was one of the functional requirements defined at the beginning of the investigation (Perng *et al.*, 2007).
- Performing the error proofing with different devices to ensure that the designed platform can work on different computers, tablets and smartphones.

BIMlegacy-2, protocol and platform, **was implemented** in the registration project of San Juan del Hospital of Valencia heritage asset. This important monument was chosen because it is a medium sized private building, it has had previous intervention projects, a variety of stakeholders, and it is accessible for the research team. San Juan heritage building has had recent restoration projects where BIM was not used. Thus, the results of this project, carried out with BIMlegacy, were compared with previous project results, where BIM was not used.

San Juan del Hospital Project entailed the participation of the following stakeholders:

Table 1. San Juan stakeholders, 2017.

Stakeholder	Years of experience
heritage architect	22
architect	15
BIM manager	4
BIM modeller	2
systems engineer	14
construction manager	12
archaeologist	18
monument manager	3
cultural broadcaster	3

contractor	20
archivist	25

Some of these stakeholders participated in the creation of BIMlegacy platform. The application of BIMlegacy in San Juan project involved the registration of the monument in the platform, the invitation of all the stakeholders, filling the fields of the platform database, building modelling, and the continuous synchronisation of both the 3D model with the work website.

The modelling consists of a laser scanning survey, a 3D modelling of this heritage asset using Revit from Autodesk Company software, 3D previous historical phases modelling, archaeology remains modelling, and the representation of materials and pathologies. Historic, archaeological, and cultural documentation was performed by the archivist and the art historian of San Juan using BIMlegacy online workspace. The HBIM model of San Juan was synchronised and updated with the BIMlegacy online workspace allowing all stakeholders to work together in real time. The project of the registration of San Juan was completed after around ten months with a total of eleven participants: heritage architect (22 years of experience), architect (15 years), BIM manager (4 years), BIM modeller (2 years), systems engineer (14 years), construction manager (12 years), archaeologist (18 years), monument manager (3 years), the cultural broadcaster (3 years), the archivist (25 years), and the contractor (20 years). San Juan case study helped in improving BIMlegacy protocol-2 by identifying possible issues related to BIMlegacy protocol practical implementation. Some important heritage processes, such the archaeology report relationship with the HBIM construction phases, and the wide variety of stakeholder's backgrounds, are examples of findings through this case study.

BIMlegacy-2 protocol and platform and its application in San Juan project were presented in a **focus group** to evaluate its effectiveness and efficiency. The focus group was carried out at the Universitat Politècnica de València with external interdisciplinary participants. The focus group participants included:

Table 2. Focus group participants, 2016.

Role	Participant description	Years of experience
BIM consultant	Architecture BIM consultant	6
BIM university professor	Knowledge of heritage architecture	18
construction engineer	BIM specialist	4
BIM architect	Experience in heritage projects	25
planning consultant	He uses BIM in his work	10
construction manager	He has experience in BIM	6
heritage broadcaster	Her background is architect	20

The questions asked were: “Which difficulties do you find in modelling historical buildings after seeing the results of this case study?”, “Do you think that the case study was documented in an appropriate way?”, “Do you think BIMlegacy is effective?” They concluded that BIMlegacy platform is useful to manage heritage projects, but they proposed further improvements for the prototype platform and protocol.

3.3.3 PHASE 3

BIMlegacy version 3, which is presented in section 4.3 of this doctoral thesis, was designed taking into consideration the knowledge achieved in San Juan case study and the external evaluation in a focus group. A new list was created synthesising the issues pointed out in the evaluative focus group and the improvements between version 2 and 3 of the protocol and platform.

The objectives of this phase were to complete BIMlegacy protocol-2 and platform-2 and correct the processes that resulted unsatisfactory in the previous phase. The techniques used to redesign BIMlegacy protocol-2 to version 3 were qualitative analysis of data with Nvivo scientific tool for scientific research, affinity diagrams, and tree structures in a hierarchical form. Some of the documentation used to complete the protocol was the Conservation Principles of Historical England had been taken into account as well as the ICOMOS Education and Training Guidelines (Maxwell, 2014).

The platform was further completed considering the stakeholders’ documented needs and the difficulties of HBIM modelling (a.e. needed to improve the definition of the archaeologist’ modelling tasks and the representation of heritage buildings pathologies). The techniques used to redesign BIMlegacy platform-2 to version 3 were qualitative analysis of data obtained in the focus group with Nvivo scientific tool for scientific research.

3.4 JOURNEY OF ETHICAL COMPLIANCE

As these methods involve human participants it is essential that ethics is also given consideration within this chapter as “ethics are critical aspects for the success of any research project” (Saunders et al, 2012, p. 208). It is important whether the researcher collects secondary data or primary data, via interviews, focus groups or workshops, that prior to commencing the research, the research is scrutinised and approved as adhering to ethical guidelines. This research gained ethical approval from the University of Huddersfield, the Doctoral Commission of the Building Engineering PhD program of the Universitat Politècnica de València, and the supervisors of this doctoral thesis. Before any interview, focus group, workshop, or data analysis a consent form was given to the participants and they signed it.

4 FINDINGS AND ANALYSIS

The results of this doctoral thesis are presented following the research method exposed in section 3.3. There are three phases, explained in sections 4.1, 4.2, and 4.3, in this investigation each of them divided in five stages, Figure 7, which is just an empty skeleton of the research method. Next, there will be an explanation of each of these phases.

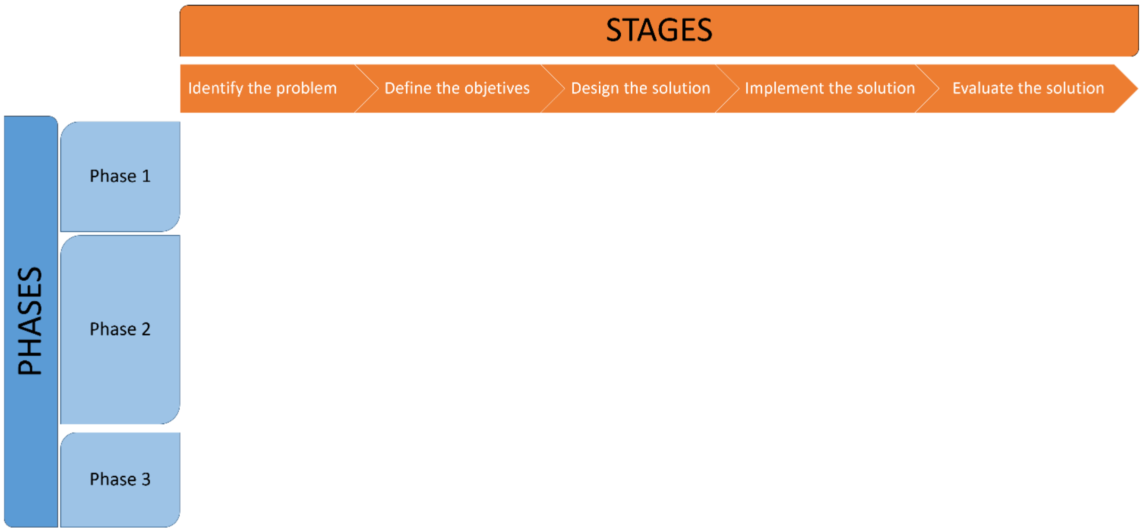


Figure 7. Stages and phases of the research design, 2015.

4.1 PHASE 1

In phase 1, the problem in heritage projects was identified through the review of the literature, the analysis of two preliminary case studies, and the analysis of the HBIM problems using the personal professional experience achieved in the BIM sector. The identification of the problem was already explained in sections *Introduction* and *Literature* of this thesis.

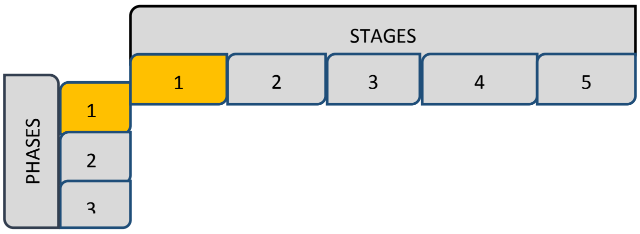
In phase 1 the general objective was to design a HBIM protocol to use in heritage interventions that improves the workflow in heritage projects, which meets with the general objective of the thesis. The specific objectives of this phase were:

(1) List heritage stakeholders.

(2) Identify the heritage buildings management needs.

(3) Identify the requirements to implement HBIM.

To achieve these objectives information of two preliminary case studies was studied and interviews were performed to heritage stakeholders of these monuments. Sagrada Familia Temple of Barcelona (Faulí Oller, 2008) and Sta. Maria's Cathedral of Vitoria (Azkarate and Solaun, 2013) stand out by their preservation tradition, path of work, and their Master Plans and these are the reasons they were chosen as exploratory cases to obtain initial data. The strategy was to include in BIMlegacy protocol-1 the tactics that have been successful in those buildings. A brief description of the main findings of the research of these two buildings is detailed bellow.



4.1.1 ANALYSIS OF TWO PRELIMINARY CASE STUDIES

4.1.1.1 Sagrada Familia Temple of Barcelona

The Basilica and Expiatory Church of the Holy Family in Barcelona is a large unfinished Roman Catholic church in Barcelona, designed by Catalan architect Antoni Gaudí (1852–1926). Gaudí's work on the building is part of a UNESCO World Heritage Site. In November 2010 Pope Benedict XVI consecrated and proclaimed it a cathedral. It is the most visited monument in Spain even though its construction continues after five generations that have already witnessed the temple's rise in Barcelona (Faulí Oller, 2008). Construction continues today and could be finished in the first third of the 21st century (see Figure 13).

Figure 13. Sagrada Familia construction works. Sagrada Familia archive, 2015.

The beginnings of the Expiatory Temple of the Holy Family, known as the Sagrada Familia, go back to 1866 when Josep Maria Bocabella i Verdaguer founded the Spiritual Association of Devotees of Saint Joseph, which in 1874 began campaigning for the construction of an expiatory temple dedicated to the Holy Family. Francisco de Paula del Villar y Lozano, the Sagrada Familia's first architect, due to disagreements with the promotors resigned from the post of chief architect and the job fell to Antoni Gaudí who proposed a new and grander design (Faulí Oller, 2008). Gaudi worked in the Sagrada Familia exclusively for almost half of his life and after the death of Gaudí, his close collaborator Domènec Sugrañes took over the management of the works. There have been different architects in chief since then coordinating the construction of this extraordinary building.

The design team is creating a HBIM model to control the maintenance of the building. The challenges of this project are to include all the contingencies that affect the construction and maintenance of the building, such as the constant visitors coming inside the building, the multiple workers that use the building every day, and the various activities carried out around the building. The management of the building is exemplary and the coordination of all the documentation of the projects is centralised (Faulí Oller, 2008). Dr. Arturo Martínez Boquera helped to meet Dr. David Puig. Bermejo, architect responsible for the structural development of Sagrada Familia's construction. Dr. David Puig Bermejo was interviewed and he supervised the author of this thesis master's thesis. The structure of the departments and building management of Sagrada Familia has taken as an example to develop BIMlegacy protocol.

This building was chosen to obtain information of the heritage management needs due to its good organisation system, the variety of stakeholders involved, and the variety of activities carried out during the life-cycle of the building.

The document analysis included design drawings, technological implementation plans, and the doctoral thesis of Dr. Jordi Fauli, architect in chief of Sagrada Familia (Faulí Oller, 2008). Figure 14, and Figure 15 are a selection of the great amount of documentation that has been analysed in this monument.

Figure 14. Historical pictures of Sagrada Familia. (Faulí 2008).

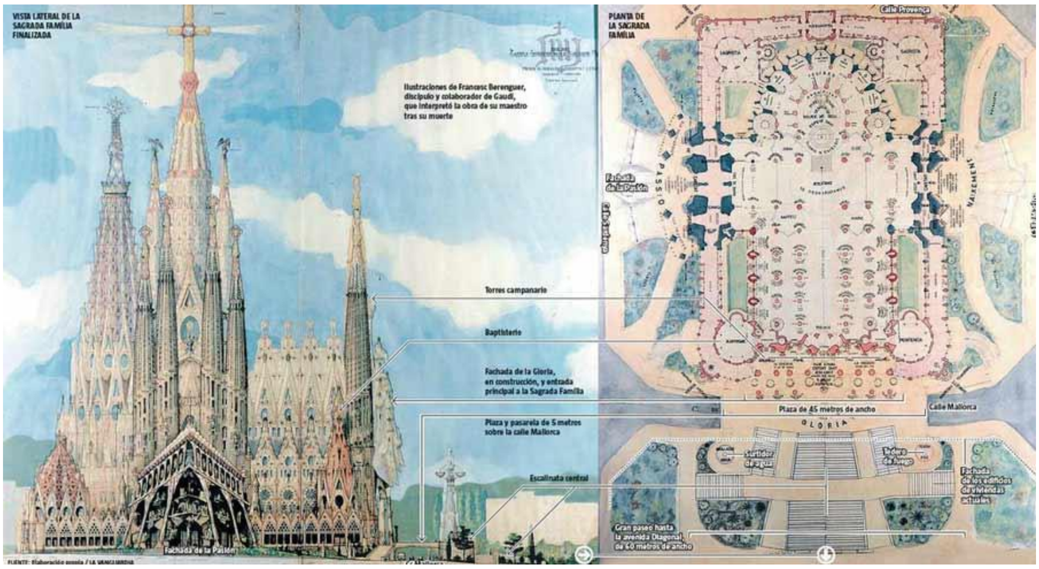


Figure 15. Architectonic survey drawn by Ramon Berenguer under supervision of the architects in chief Isidre Puig Boada and Lluís Bonet. Doctoral thesis of Dr. Jordi Fauli (Faulí 2008).

Sagrada Familia was visited two times, one to get involved with the team, construction works, and to consult documentation; and the second one to perform interviews to strategical stakeholders: an architect of Sagrada Familia (13 years of experience), a construction manager of Sagrada Familia (8 years), a technical architect (18 years), and an archivist of Sagrada Familia (25 years). The questions asked included: What departments are involved in managing your monument? Which stakeholders are involved? How do you archive the produced information?

These interviews have been transcribed and analysed with the scientific tool named NVivo (Annex 3. Qualitative data analysis using Nvivo), specifically designed for qualitative research (Robins and Eisen, 2017). From this analysis some ideas emerged to design BIMlegacy protocol-1. The analysis of this monument assisted to generate the list of heritage stakeholders, section 4.1.2 and to create the list of heritage buildings management needs, section 4.1.3.

4.1.1.2 Cathedral of Santa María of Vitoria-Gasteiz

It consists of a group of buildings for different purposes built during distant historical eras. The church, which dates from the thirteenth century, is based on a Latin Cross floor plan with a central nave and aisles on either side covered by ribbed vaults and features a generous transept and apse (Arriaga and Lozano, 2012). The building is managed by the Santa María Cathedral Foundation that is the institution created to manage and develop the Master Plan for Comprehensive Restoration of the most emblematic church with the greatest historical value in Vitoria-Gasteiz (Azkarate and Solaum, 2013). The quality of the Master Plan has been recognised by the European Union, the Vatican, and the Ministry of Culture and by prestigious national and international forums. It was awarded the Europa Nostra Prize (2002), the highest European award for recovery and conservation of the cultural heritage. Sta. María's Cathedral is a common typology of building in Europe, Figure 16.

Figure 16. Santa Maria celling view. Iñaki Koroso personal archive, 2016.

The research, documentation and restoration of the cathedral has been an unbeatable opportunity for an exchange of ideas and knowledge between different teams working in the field of conservation of the built heritage. This fact has turned the worksite into a nursery of ideas that transcends the artefact itself and is now embodied in numerous initiatives related to the conservation of the historical and architectural heritage (Azkarate and Solaun, 2013). All the information of Santa María is centralised in a CDE that is linked to CAD models. They developed a simple protocol to carry out their work (interview with Iñaki Koroso 2016):

1. Modelling.
2. Exportation of the 3D model with texturized areas and its alphanumeric and graphic database.
3. Generation of virtual models to upload online.

In June 2000, when Santa María Cathedral implemented a new system of visits which visitors wearing a helmet could tour a church under construction, nobody suspected that with the passage of time this slogan would become a benchmark with significant repercussion on society. Thus, they have been innovating in the use of new technologies in heritage buildings.

The document analysis included design drawings, technological implementation plans, and monument's databases as shown in figures below Figure 17, and Figure 18.

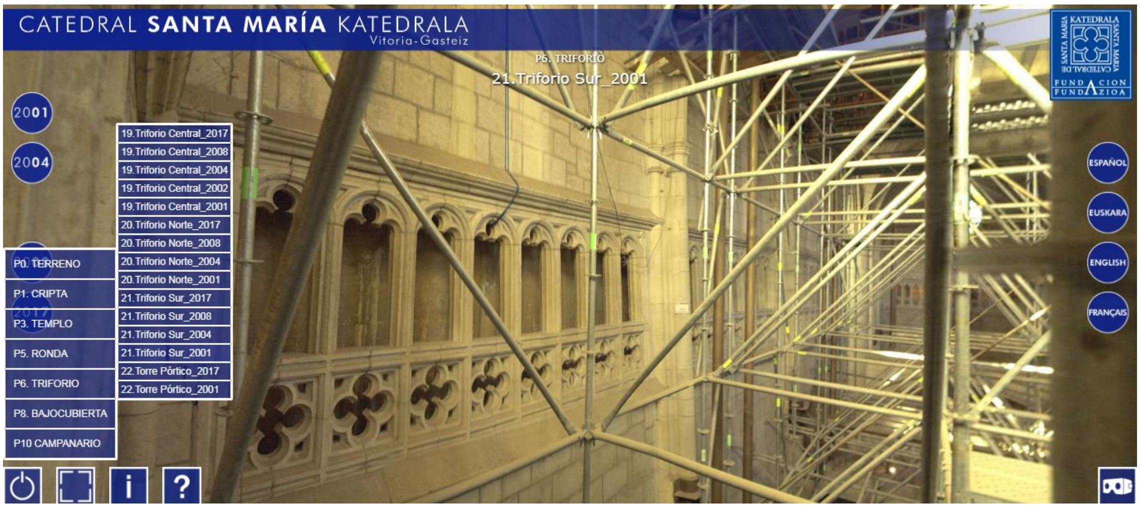


Figure 17. Santa Maria virtual visit platform structure. Santa María website. 2016.

The elements of the proposed layout on the Spanish National Plan of Cathedrals (1997) that was applied in Santa María were taken as reference (Combalía-Solís and Jiménez Cuenca, 1997). This Plan includes subjects such as: building's analysis, needs, and risks; application of intervention criteria; coordination of actions; performances programming documentation, research, protection, conservation, restoration, training, accessibility, and dissemination; implementation, maintenance, and monitoring.

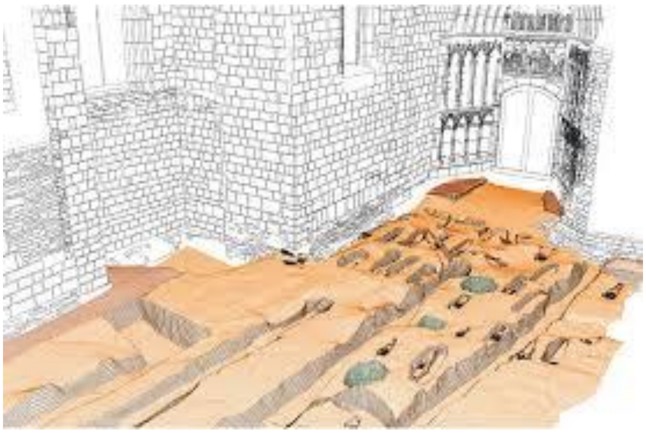
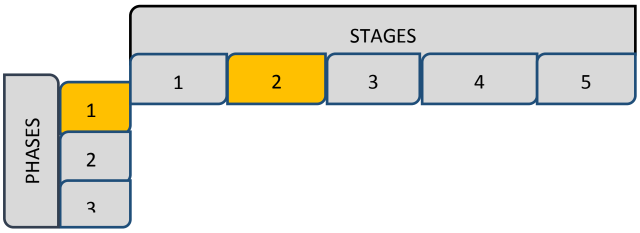


Figure 18. Archaeological representation of Sta. Maria using 3D registration. "Space throughout time, application of 3d virtual reconstruction and light projection techniques in the analysis and reconstruction of cultural heritage" (Arriaga y Lozano 2009).

Two stakeholders of Santa María were interviewed through skype: a topographical surveyor of Santa María (22 years), and a heritage diffusion expert of Santa María (12 years). The objective of these interviews was to achieve information related with the use of 3D virtual reconstruction and facility management in the monuments. The questions asked included: Which stakeholders are involved? How do you archive the produced information? The stakeholders of Santa María are experts in managing the facility management with relevant success, so important information was obtained from these interviews.

These interviews have been transcribed and analysed with the scientific tool named NVivo (Annex 3. Qualitative data analysis using Nvivo). From this analysis some ideas for the design of BIMlegacy protocol-1 have been achieved that assisted to generate the list of heritage stakeholders, section 4.1.2, and the list of heritage buildings management needs, section 4.1.3.

4.1.2 LIST OF HERITAGE STAKEHOLDERS



The first step to create BIMlegacy protocol-1 was to list the heritage architecture stakeholders, the tasks that they carry out, and the responsibilities that they have. A list of heritage stakeholders was obtained out of the analysis of the documentation of both preliminary case studies Sagrada Familia of Barcelona and Santa María of Vitoria and the information achieved from the interviews. The doctoral thesis of Dr. Jordi Fauli, architect in chief of Sagrada Familia, was one of the analysed documents that most clearly specifies the involved stakeholders in a successful heritage project (Faulí Oller, 2008).

The interviews and the main findings of the documentary analysis have been transcribed and analysed with the scientific tool named NVivo. From this analysis, the following stakeholders have been identified as is shown in Figure 19: client, administration, historian, archaeologist, architect, construction engineering, engineer, contractor, suppliers, construction manager, restorer, monument manager, and project manager.

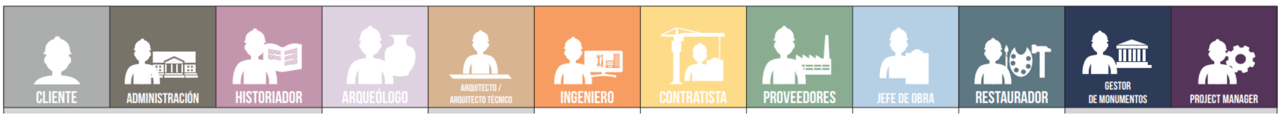


Figure 19. Heritage stakeholders identified through the documentary analysis. 2016.

Each stakeholder identified from the analysis of the documentation of the case studies was coded with a colour and the same colour was used for the tasks that each of them carries out. The tasks and the stakeholders were coded looking for affinities between interviews and documentation. As a result, a scheme detailing the tasks that each stakeholder develops was created, Figure 20.

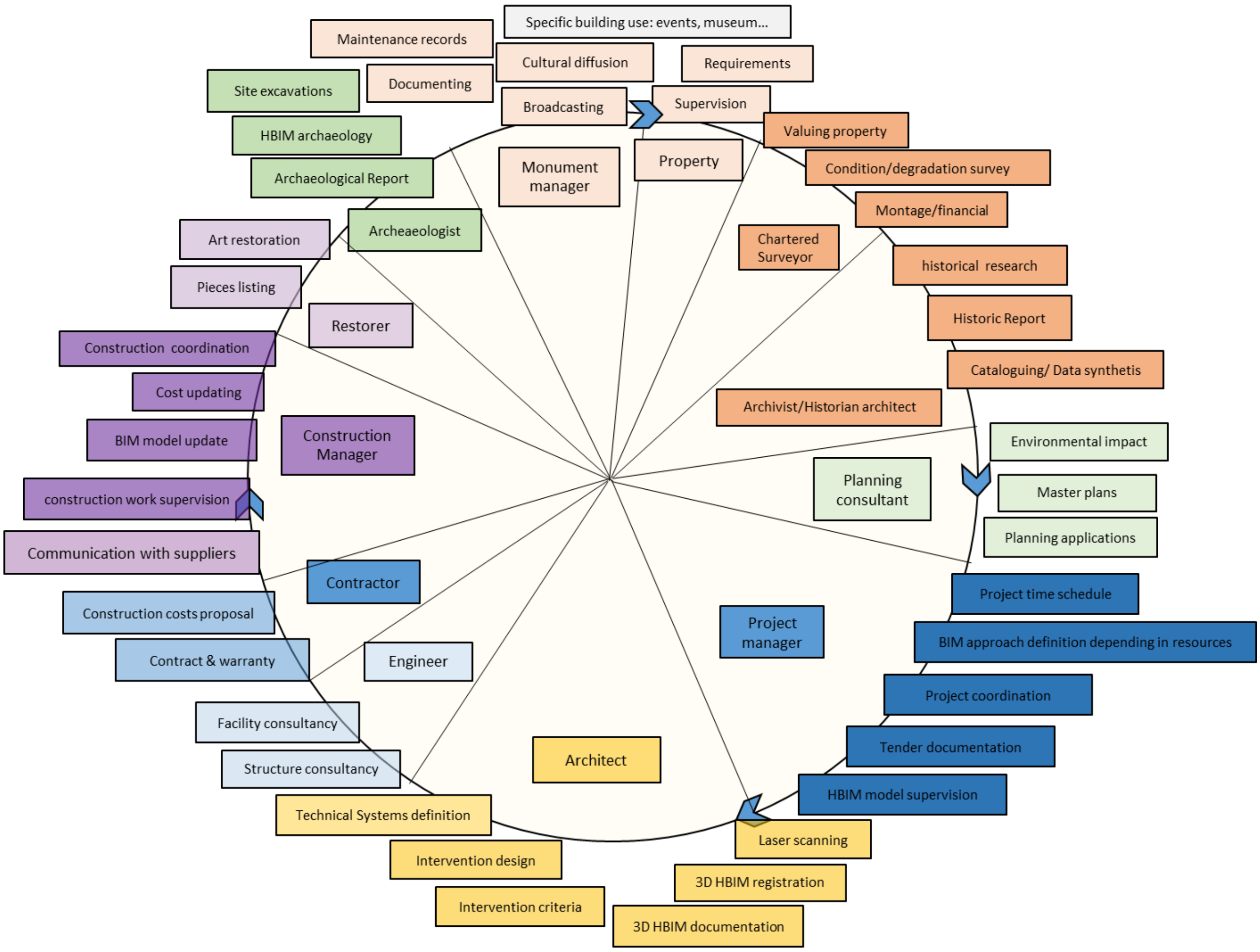


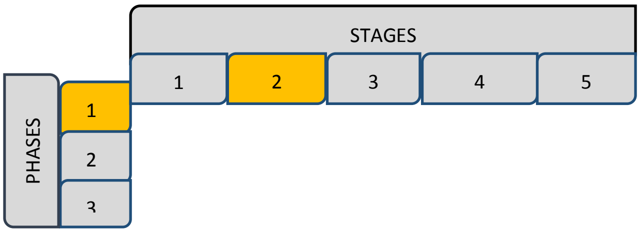
Figure 20. Stakeholders and tasks that they develop, 2016.

As a result of the analysis carried out, the responsibilities diagram was also developed. It is divided into stages of the life-cycle and tasks of the life-cycle. In the top of it has the stakeholders and the involvement of the stakeholders within the tasks is represented with the letters R (responsible), I (involved), and S (supervisor), Table 3. The colour codification is maintained from one diagram to the other.

Table 3. Heritage stakeholder's responsibilities during the stages of a building life-cycle, 2016.

Stage	Task	Monument manager/ owner	Government Agents	Architect	Historian/ Documenter	Archeaeologist	Engineers	Contractor	Construction Manager	Manufacture/ Suppliers	Restorer
Previous studies	Master planning check	S		R				S			
	Search financial support	R	I					I			
	Data research	I	I	S	R	S					S
	Site excavations	I		I	I	R					
	Archaeological Report	I		I	I	R					
	Historic Report	I		I	R	I					
	Cataloguing	I	I	S	R	S					
	coordination	R		S				S	S		
	Law Assistance	S	R	S		I		I			
Architectonic Survey	Laser scanning-Photo 3D	I		R		I					
	HBIM generic modelling			R							
HBIM Registration	Historical Phases			R	S	S					I
	Pathologies-stratigraphy			R	I	S					I
	HBIM modelling			R	I	S	S	I	I		
	Archaeology modelling			I	I	R			I		I
	parametrization			R		I	S		I	I	
HBIM Documentation	Master plan data	I	I	R	I		I	I			
	Historic-archaeological data	S		S	R	S	I				
Restoration design	Restoration Criteria	I		R	I	S	S	S	S		I
	Design Development			R			S	S	S	I	S
	Technical Design			R		I	S	S	S	I	S
	Structure consultancy	I	I	S		I	R	S	S	S	
	Facility consultancy	I		S		I	R	S	S	S	
Pre-Restoration	Production Information		I	R	I	I	S		I		I
	Manage Tender Documentation	I	I	R			S	I	I		
	Council Supervision	I	R	S			S	I	I		
	Technical Systems definition			R			S	S	S	S	
	Construction costs	I		I		I	I	R	S	I	I
	Restoration Time schedule	I		I			I	S	R	I	
Restoration	Mobilisation	I		I				R	S		
	Restoration to practical completion	I		I				R	S	S	S
	Restoration supervision	I		R			S	I	I		
	Art restoration	I		I				I	I		R
	Art Pieces listing	I		I					I		R
	Restoration coordination	I		I				S	R		I
	Cost updating	I		I			I	S	R		I
	BIM model update			S			S	I	R		
Use	Post Practical Completion	S	I	S			I	R	S		I
	Maintenance	R		I			I	S			I
	Broadcasting	R		I	I	I					

4.1.3 LIST OF HERITAGE BUILDINGS MANAGEMENT NEEDS



The second process to create BIMlegacy protocol-1 was to identify the needs of heritage projects with the perspective of the HBIM implementation. The source of data to obtain the list of heritage buildings management needs were the two preliminary case studies. The information obtained from these preliminary case studies was registered with the tool Nvivo (Annex 3. Qualitative data analysis using Nvivo). To obtain an ordered the list of heritage management needs it was necessary to organise the statements recorded in Nvivo coming from the documentary analysis of Sagrada Familia and Santa María, and the interviews of their stakeholders. As is explained in section 4.1.1 the document analysis included design drawings, technological implementation plans, and monument's databases.

A wealth of information was recorder with Nvivo out of these two preliminary case studies. To obtain a list of heritage buildings management needs, which was the main objective, the strategy was to order this information in categories, to extract objectives to improve heritage projects, and to obtain the list of heritage buildings management needs. A further explanation of this process is described below.

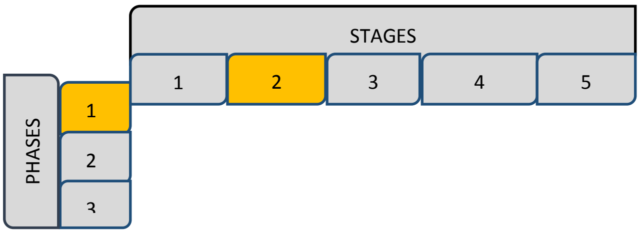
To order the information it was necessary to create eight categories with the statements obtained from the analysis in Nvivo of the information generated in Sagrada Familia and Santa María, these categories were: historical, economic, fiscal, architectural projects, promotional tourism, management activities, and environmental working needs of heritage architecture. Other sub-categories were established such as culture, tourism, social dissemination of historic properties, current socio-technical needs, Master Plans demands, and data management systems. The Nvivo statements organised in categories were translated into a list of objectives to improve heritage projects using the affinity tool of Nvivo, which are presented in Table 4. Some of the objectives obtained in this affinity process and presented in Table 4 were "To obtain the departmental structure of the heritage process" or "To contemplate construction and use phase including touristic uses".

The information recorded in Nvivo was also used to get a list of heritage management needs that are shown in Table 4. The management needs are directly related to the list of objectives, also presented in a column of Table 4, to improve heritage needs. Each objective has is translated into a management need. This table will raise some of the assumptions of the BIMlegacy protocol-1 that are further explained in section 4.1.5.

Field	Objectives to improve heritage projects	Heritage management needs
Sagrada Familia's Temple	To obtain the departmental structure of the heritage process	Flowchart structure: preliminary study of existing graphic survey, design and construction.
	To have an addition system	Flexible protocol
	To contemplate construction and use phase including touristic uses.	HBIM construction management BIM design options
	To maintain and monitor buildings	Maintenance data connection and disposal as 3D model data container.
	To create a corporative image and graphic standardization	Graphic image in the HBIM temple
	To represent of patrimonial characteristic elements such as gothic columns, arcs, vaults…	Create BIM historic families
	To allow for the level of development control of each step: preliminary studies, project, and construction	Contemplate the whole life-cycle of the building.
	To contemplate the principles of the historical memory	Integrate heritage regulations within the BIMlegacy protocol.
	To recognize the value of the ancient buildings and the Monumental Master Plan's principles	Integrate Monumental Master plan principles within the BIMlegacy protocol.
Sta. María's Cathedral	To integrate management: architecture, construction, culture, and tourism	HBIM 3D model connection with an online platform
	To take into consideration the building Master Plan	To connect Master Plans matters in the 3D HBIM model
	Importance of geometric design in the buildings' generation	Geometrical BIM model G3 model
	To update facilities and structure	Facilities and structure modelling G4
	To synchronise the team members' work	Central model and sub-projects
	To create an HBIM template; there are no HBIM templates in the market	Design a template with the characteristic elements of the historic buildings
	To model structural seats, deformities, and stone pathologies.	BIM families representing deformities Free BIM modelling that represents the pass of time

Table 4. Proposals for BIMlegacy -1 coming from the monuments needs analysis, 2016.

4.1.4 LIST OF REQUIREMENTS TO IMPLEMENT HBIM



The third process to build BIMlegacy protocol-1 was to list the requirements to implement HBIM. The requirements to implement HBIM were obtained from:

(a) The analysis of the literature review. The articles and reports found in the literature review were recorded, organised and analysed with Nvivo through statistical repetition tool of and affinity relation tool of the software.

(b) The professional experience working with HBIM. The professional experience in HBIM was also recorded in a series of statements in Nvivo obtained out of multiple HBIM project developed in different companies: Emma Create Architecten in Amsterdam and Vic F. Group in Valencia.

4.1.4.1 List of requirements to implement HBIM from the literature review

The selection of 65 articles coming from the literature review, section 2 of this thesis, was inserted in Nvivo and analysed with different tools. Nvivo software is a qualitative scientific tool that helps researchers to generate affinity tables and diagrams (Annex 3. Qualitative data analysis using Nvivo). Basically, this tool substitutes the manual excel tables that academics use to do for qualitative research (Robins and Eisen, 2017). Firstly, the articles were sorted into these five groups ‘’HBIM’’, “Scan to BIM”, “BIM Management”, “BIM to TIC/MAR”, and ‘’BIM social’’. Then, these large clusters were sorted into subgroups for easier management and analysis. For example, the “HBIM” group was sorted into the following subgroups: HBIM benefits, HBIM issues, HBIM protocols/methods, HBIM CDE.

During the literature review, in the articles that explain HBIM protocols, methods or platforms the following aspects were studied: the life-cycle coverage (“design”, “construction”, “use”); the kind of artefact that was designed (“method”, “protocol”, “platform”); the group of people it was designed for (“architects”, “owners”, “tourism”); and if it was tested in real cases.

Each article was re-read underlining in Nvivo the sentences that represent the following categories: the scope of the study, definition of HBIM, HBIM benefits, HBIM issues, HBIM protocol or guide used as reference, HBIM platform or CDE used, and recommendations for the application of HBIM.

Each category was coded with a colour and a letter code as seen in Figure 21. The articles that explain case studies, which that did not fit in any of these categories, were listed apart. The HBIM case studies from the literature were listed and valued the possibility of including their modelling techniques in BIMlegacy protocol-1.

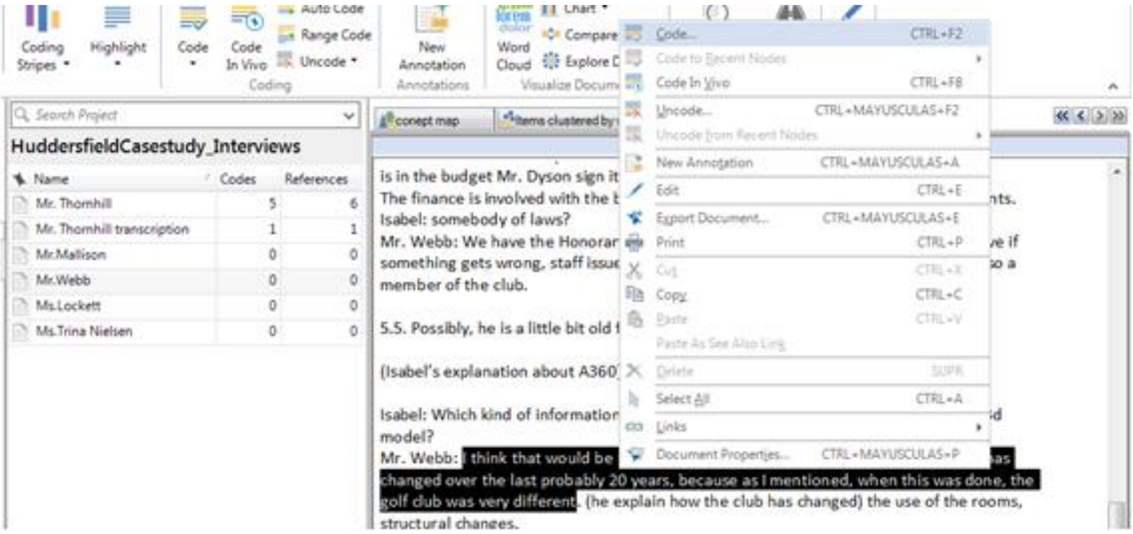


Figure 21. Nvivo analysis of an article underlining with codes the different categories. 2016.

After underlining with Nvivo the 65 papers, the groupings of each of the categories were automatically obtained and the similarities were overlapped. For example, some of the HBIM benefits underlined in different articles meet in the meaning, thus, the software marks possible coincidences. This filtering process was semi-automatic since some of the automatic groups created needed to be manually reviewed.

Table 5. Proposals of BIMlegacy -1 coming from the state of the art, 2015.

Field	Objectives	Work processes proposed
HBIM	-To include historical phases, pathologies, archaeology, and stratigraphic study	-Historical phases definition -BIM Free Form Modelling
Scan to BIM	-To include point clouds in BIM space.	-Laser scanning -Import point cloud
BIM Management	-To add data tables and time schedules	-BIM data tables, BIM information tables and online platform
BIM to TIC/MAR	-Integrated management -Internationalization	-Maintenance phase -Video, computer graphics, and renders broadcast
BIM social	-Productivity through the human factor -Legislation knowledge	-Server creation, nomenclature and normative inclusion

It was necessary to obtain a very simple table with the main objectives of each of the five groups according to the statements of Robins and Eisen (Robins and Eisen, 2017). Table 5 is the result of this filtering and simplification process. It has two columns, one has the objectives of each of the five groups and the other column has the processes required to carry out these objectives. These work processes were transformed into the boxes of the tree diagram that will be developed in section 4.1.5. Some of the analysed HBIM articles proposed HBIM flowcharts that were taken into account to desgin BIMlegacy protocol-1. The most relevant flowcharts found were: Figure 22 Diagram representing the steps described by RIBA Plan of work; Figure 23 the classical BIM layout divided in technology, process, and policy; and Figure 24 the BIM stages in a project. These flowcharts are further explained bellow:

Figure 22. Steps of the BIM project according to RIBA Plan of work, 2013.

Figure 23 represents the BIM layout divided into technology, process, and policy. This is an example of flowchart where the square boxes are processes, the files can be imputs or outputs and the romboid figure are decisions to make. This grapics are usually part of the BIM Execution Plan (BEP), previously explained, and are usful to explain the BIM uses.

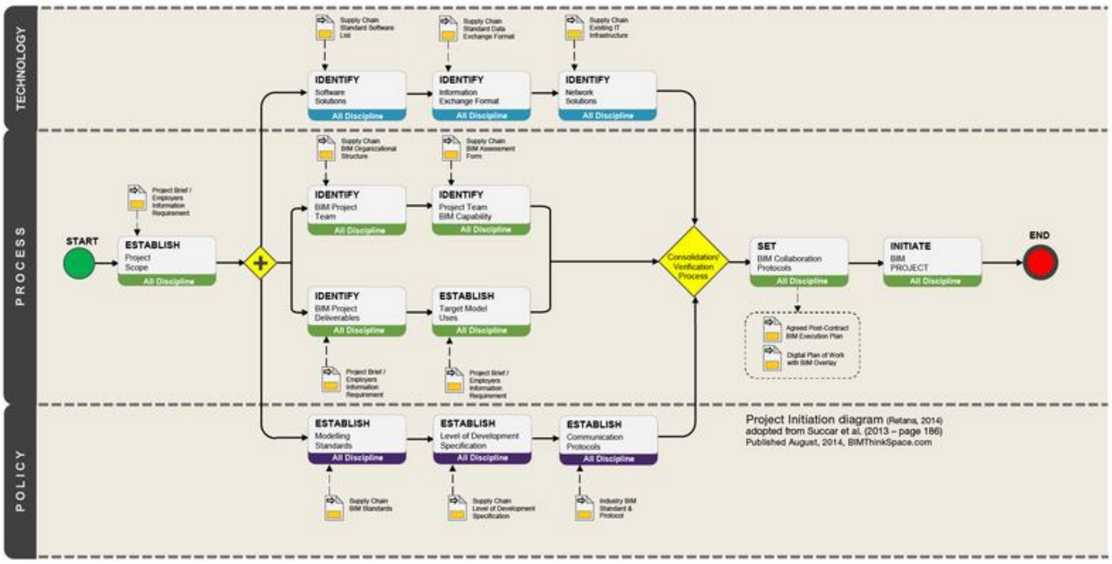


Figure 23. BIM layout according to RIBA Plan of work, 2013.

Figure 24 represents BIM different stages of maturity in a project in terms of collaboration according to Architectural, Engineering and Construction UK (AEC) in 2007. The AEC (UK) Initiative was formed in 2000 to improve the process of design information production, management, and exchange. In Figure 24 BIM level 2 is the model-based modelling stage where the model is shared between different disciplines and it should have four or five dimmensions. BIM level 3 is the integrated practice what entails multi-dimensional model, clash detection (detecting elements that intersect other elements of different disciplines, for example a pipe with a column), and lifecycle costing.

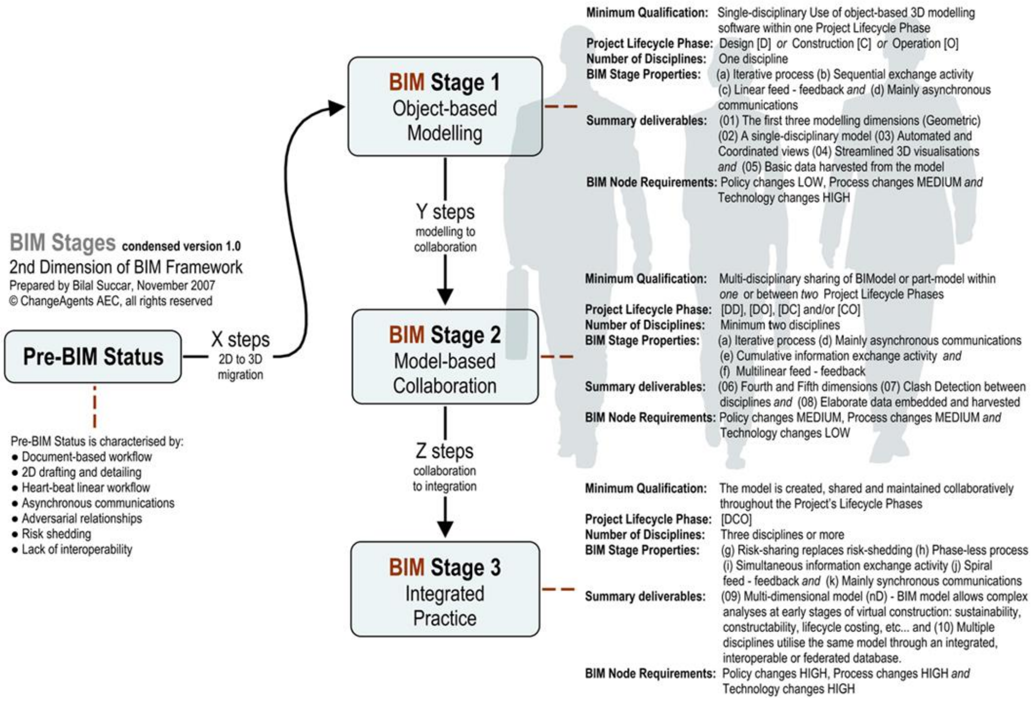


Figure 24. BIM stages according to UK BIM Standards for the Architectural, Engineering and Construction (AEC) industry (2007).

4.1.4.2 List of requirements to implement HBIM from the HBIM professional experience

The possibility to include the BIM personal experience achieved by the PhD candidate during the last six years was considered very useful since one of the conclusions of the literature review was that more practical experience is required to evaluate certain HBIM benefits and difficulties. The professional experience comes from two companies: Emma Create Architecten in Amsterdam, a pioneer architectural studio to implement BIM and HBIM in Europe, and Vic F. Group in Valencia, which is a construction company dedicated to refurbishments and historic buildings conservation. In such companies BIM was used as methodologic system to develop the projects and constructions. In the first company the position was architecture BIM modeller and later on BIM manager, and in the second company the position is BIM implementer and BIM manager.

Not all the HBIM projects on which the author of this thesis worked were recorded, just those ones belonging to the last four years. The HBIM processes, difficulties, and proved benefits of the HBIM professional projects were recorded using OneNote software of Windows as shown in Figure 25. OneNote has three columns, the first one has the list of projects, the second one is the folders of notes of each project, and the third one includes the notes taken during the projects. There are very informal notes such as the difficulties of modelling or the duration of certain modelling tasks.

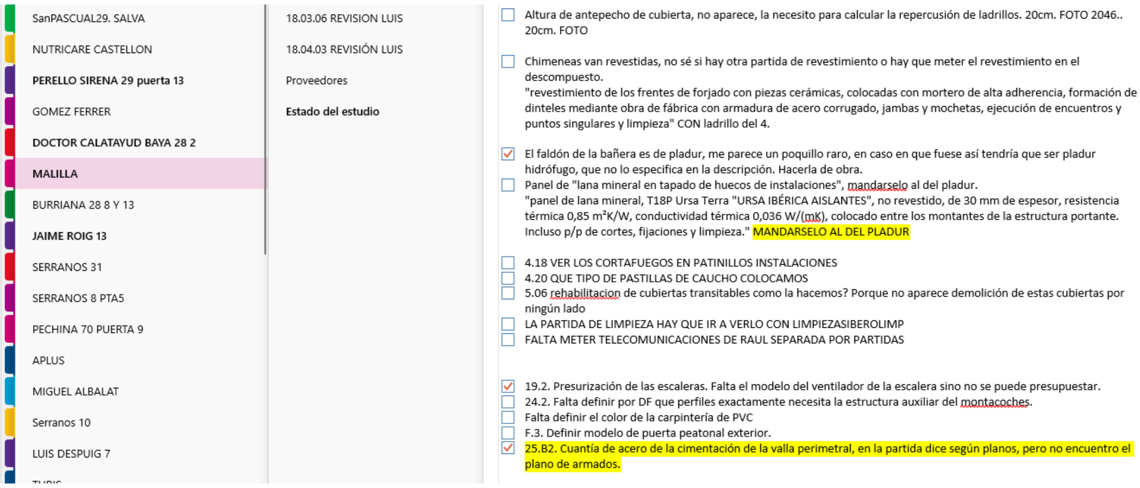


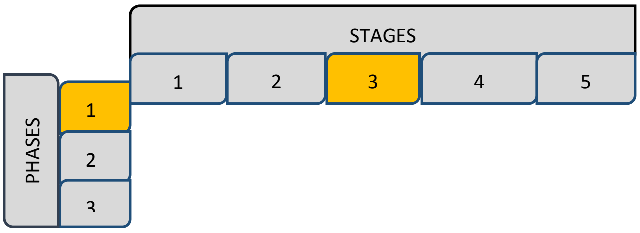
Figure 25. Notes taken during the HBIM professional projects carried out with HBIM, 2014-2018.

The large number of notes recorded was imported to Nvivo software to generate the affinity analysis and eliminate the duplicated or similar data. HBIM difficulties were summarised in a series of statements and solutions as shown in Table 6. This table has two columns, the first one contains the difficulties to implement HBIM detected from the analysis of the BIM experience and the second column contains possible solutions to these difficulties also obtained from the analysis of the BIM professional experience. These difficulties and solutions were divided into three rows regarding the phase of the life cycle: design, construction, and use.

Table 6. Proposals for BIMlegacy -1 coming from the professional experience analysis, 2017.

Phase	Difficulties	Solutions
Step		
Design	-To have a flexible software to generate creative designs -To create high quality drawings out of HBIM software -To document the building correctly with HBIM software	-To use HBIM masses and in situ families -To use elaborated HBIM templates -To link the archivist databases with the HBIM models
Construction	-To link the construction budget with the HBIM models -The construction manager has not the HBIM knowledge to modify HBIM models.	-To use specific plug-ins to synchronise the construction budget -To train construction managers on site to improve their HBIM knowledge.
Use	-To have a simple HBIM model to control maintenance -To control heritage needs related with tourism control, and conservation of the monument	-To purge and simplify HBIM construction models before giving it to the property. -HBIM models can be used to control tourism access and to preserve the monument condition.

4.1.5 PROCESS OF DESIGN BIMLEGACY PROTOCOL-1



BIMlegacy protocol-1 was designed using affinity diagrams and tree structures to organise all the statements obtained in the list of heritage stakeholders, section 4.1.2, list of heritage buildings management needs, section 4.1.3, and list of requirements to implement HBIM, section 4.1.4. The affinity diagrams and tree diagrams were organised and grouped data in a hierarchical form.

With this three summarising tables an affinity diagram was created to organise ideas following the steps recommended by Mizuno (1993):

- Record each idea on notes, which were Table 4, Table 3, and Table 6.
- Look for ideas that seem to be related. Determine groupings.
- Organise. Place each factor or idea beneath a category. Try combining duplicate issues to simplify.
- Sort tables statements into groups until all ideas in boxes have been used. Decide on a logical set of related categories.
- Analyse and share. Step back and look at the diagram. Analyse if it can help you make a decision or see things more clearly.

Designing BIMlegacy protocol-1 was a process were multiple diagrams were generated using Nvivo graphics, Visio from Windows, and even hand-sketched diagrams. Relating all the ideas was a complex process even though useful qualitative techniques, tools, and software were utilised. The process of creation is detailed below.

The ideas of the three tables that seemed to be related were grouped into different diagrams. As an example, Figure 26 represents an affinity diagram grouping processes per life-cycle stage. Colours represent the different stages of the life-cycle. These colours legend of Figure 26 was kept in all diagrams and flowcharts.

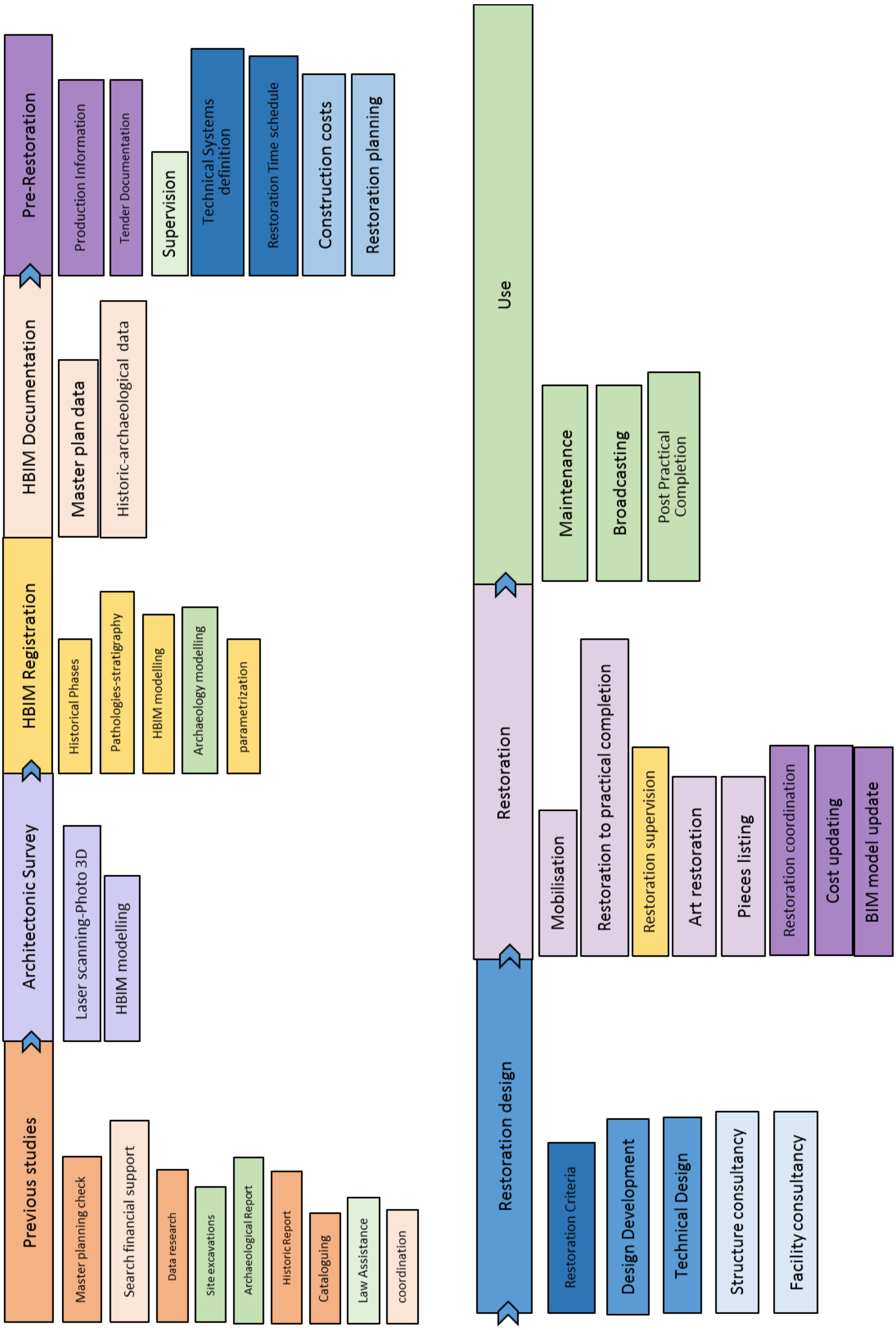


Figure 26. Affinity diagram grouping processes per life-cycle stage, 2016.

The statements were organised as groups until all ideas of Table 4 and Table 6 were used. Figure 27 represents the affinity process of the ideas coming from Table 4 and Table 6. The legend of colours of the diagrams was represented in Table 7.

To allow the visualization of all the information analysed, just the statements in the tables were inserted in this diagram. The diagrams of each table were combined considering a series of criteria such as the satisfactory processes of historic buildings. Figure 27 represents the affinity of the HBIM processes related with some processes of historic buildings. This figure took the structure of *Figure 23. BIM layout* which contained the classical division of BIM processes (technology, processes and policy), and incorporated heritage fields and heritage stages such as previous studies using point cloud to document the heritage building or modelling all disciplines (architecture, archaeology, restoration) in one coordinated model.

Table 7. Legend of colours in the diagrams. Each stakeholder is represented by a colour, 2016.

Property	pink
archivist	orange
architect	yellow
Archaeologist	green
engineer	Light blue
contractor	blue
Project manager	Dark blue

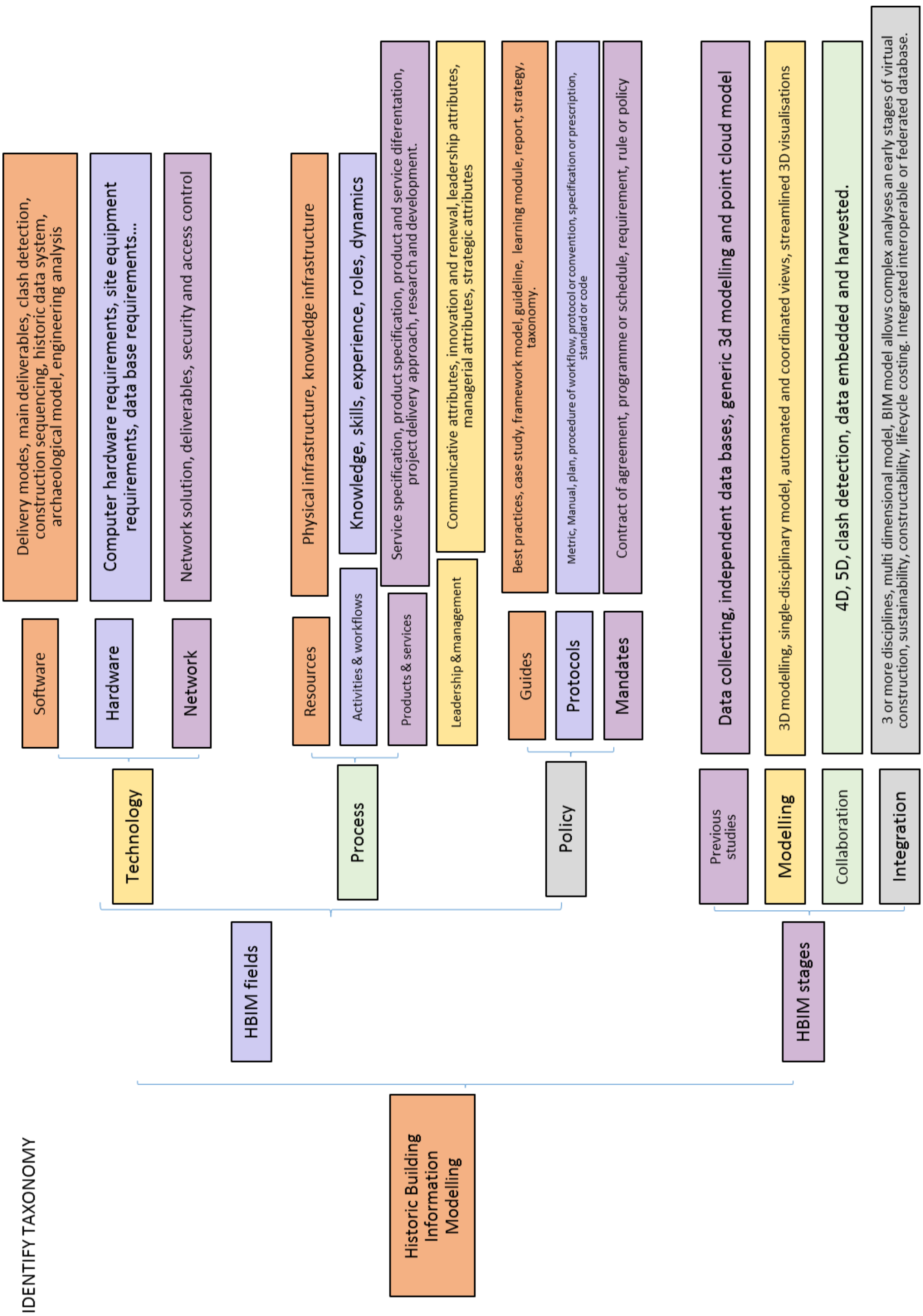
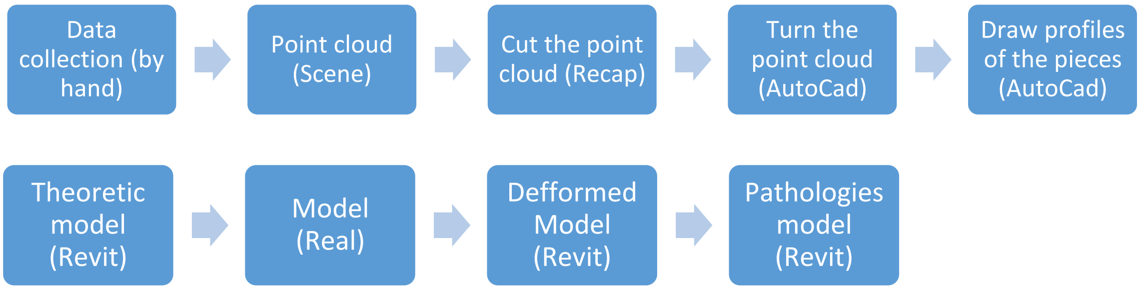


Figure 27. Tree diagram that orders processes with aspects of HBIM, 2016.

Some specific processes were ordered using hand-sketched flowchart since the affinity relations created by Nvivo were not successful or did not make sense when checking them. Figure 28 is a hand-sketched flowchart that illustrates the Scan to BIM process in the design.

The processes are represented with rectangles and the required software in each process is written down with black pencil and in capital letters.



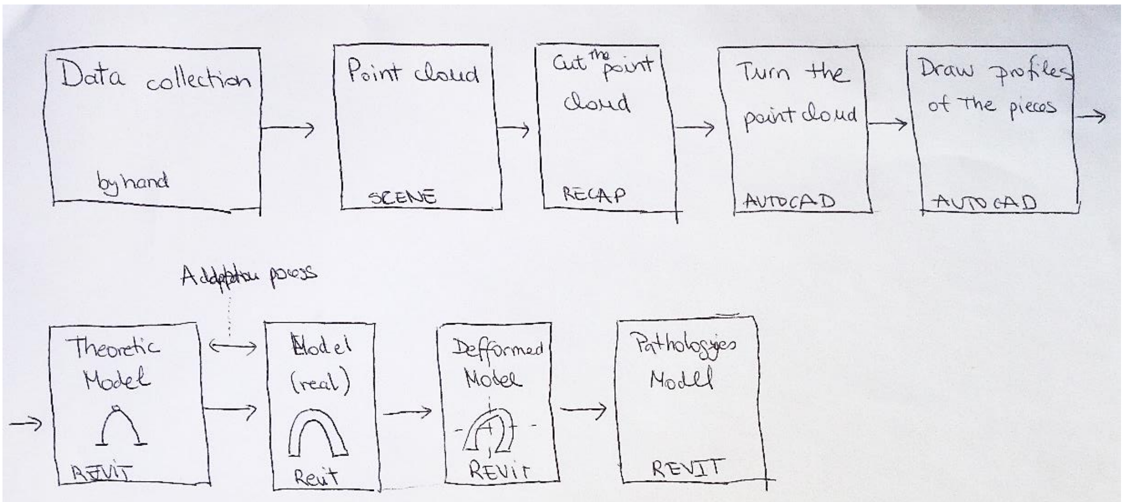


Figure 28. Hand-sketched flowchart illustrating specific processes not included in Nvivo, 2016.

In the literature review there were few articles that described partial HBIM processes such as Figure 29 that is a HBIM processual flowchart from an empirical case study led by Nieto (2016). It outlines the process of developing an advanced HBIM model. This involves two distinct steps: first, a survey for gathering 3D data using laser scanning and photogrammetry (Murphy *et al.*, 2009); second, the development of a building information model for the management of architectural heritage. The main proposal of this research sets three action levels: the aforementioned survey in order to adjust the images to the model by means of photogrammetric rectification; the identification and cataloguing of irregular pieces; and finally the management of information Nieto (2016). The partial HBIM flowcharts founded in the literature review were compared with our flowcharts to complete some parts or missed processes.

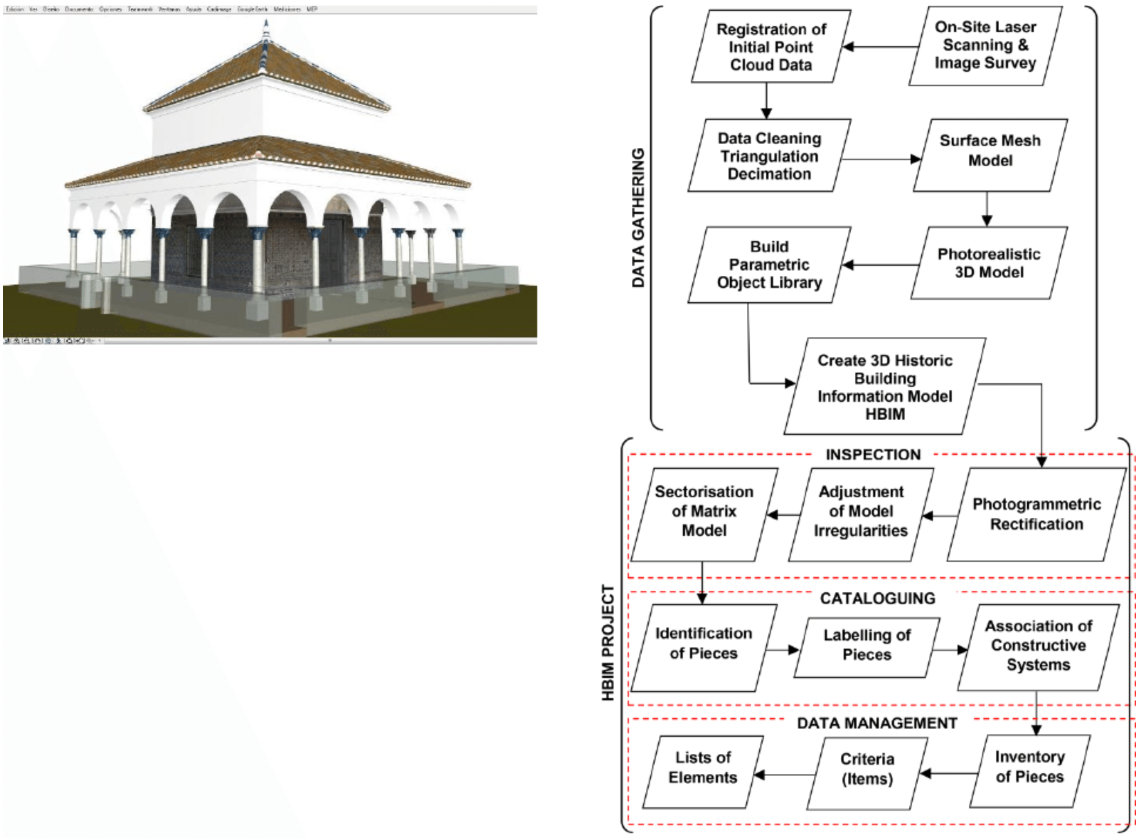


Figure 29. The HBIM processual flowchart proposed by Nieto. (2016).

The last part of the affinity process consisted of deciding a logical set of related categories, which was generated using Visio software of Windows. It was a complex process that took a long time and needed multiple sub-diagrams to order the ideas. Figure 30 is an example of these sub-diagrams or work diagrams requiring careful thought to analyse multiple processes, outputs, and requirements. The result was a cause and effect diagram that grouped all the similar processes and outputs in each stage of the life-cycle. Table 7 is the legend of colours of the diagrams used in the thesis.

In Figure 30 the thick arrows of the figure mean the transition to different life-cycle stages of a heritage building (a.e. registration, project design, and technical definition of the project). Thin arrows connect stakeholders (a.e. archivist, architect, monument manager) with processes such as “architect” with “pieces listing” or “contraction manager” with “contract and warranty”. The colours mean stakeholders as was previously mentioned in Table 7.

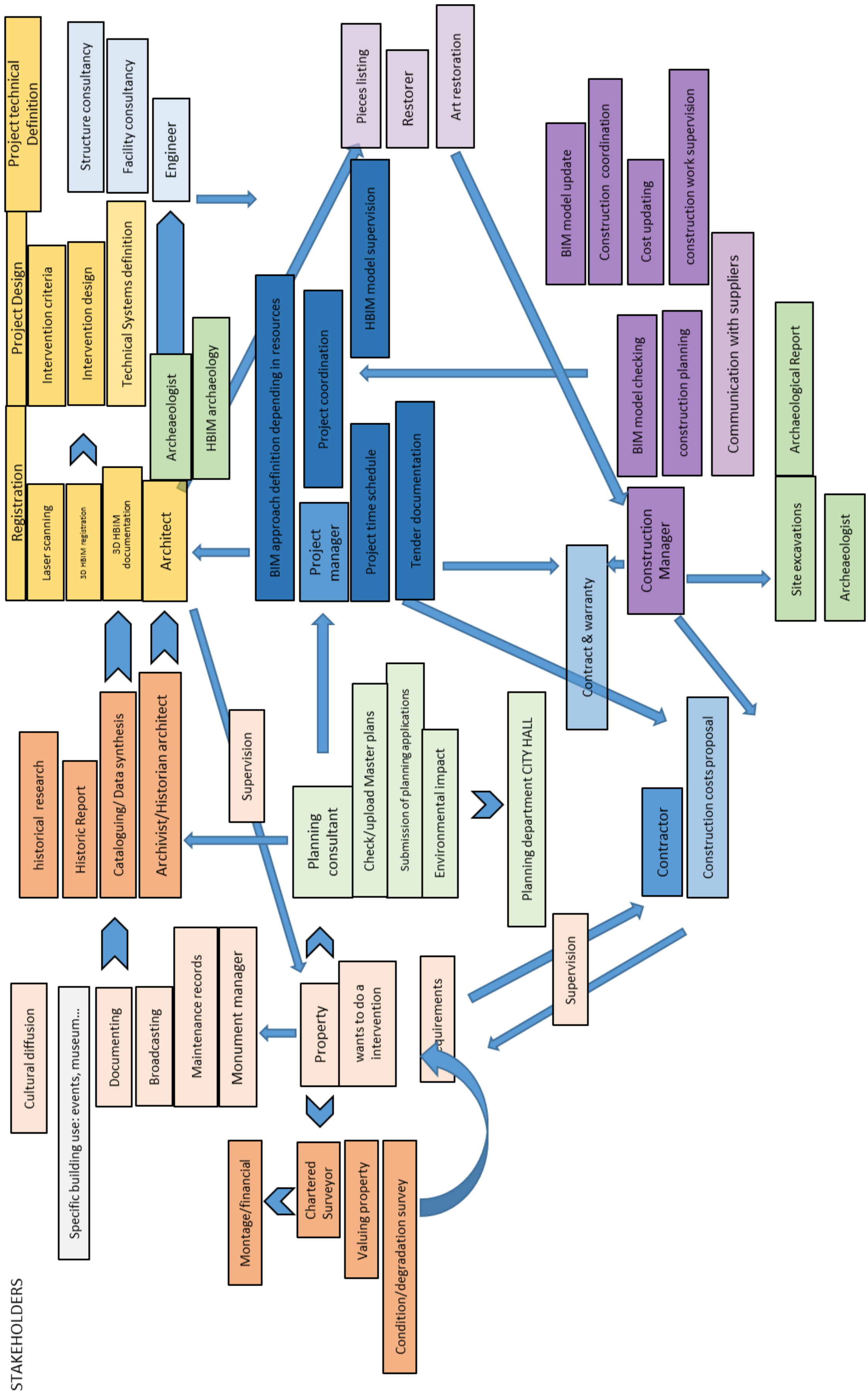


Figure 30. Process of relating the stakeholders with the heritage processes and HBIM processes, 2016.

This diagram was improved using a tree diagram to organise data already grouped in a hierarchical form by the affinity diagram. The flowchart related the concepts of Table 4, Table 5, and Table 6, to propose a preliminary BIMlegacy protocol-1, which was the result of this tree diagram after three improvements due to the PhD supervisor’s corrections, Figure 31.

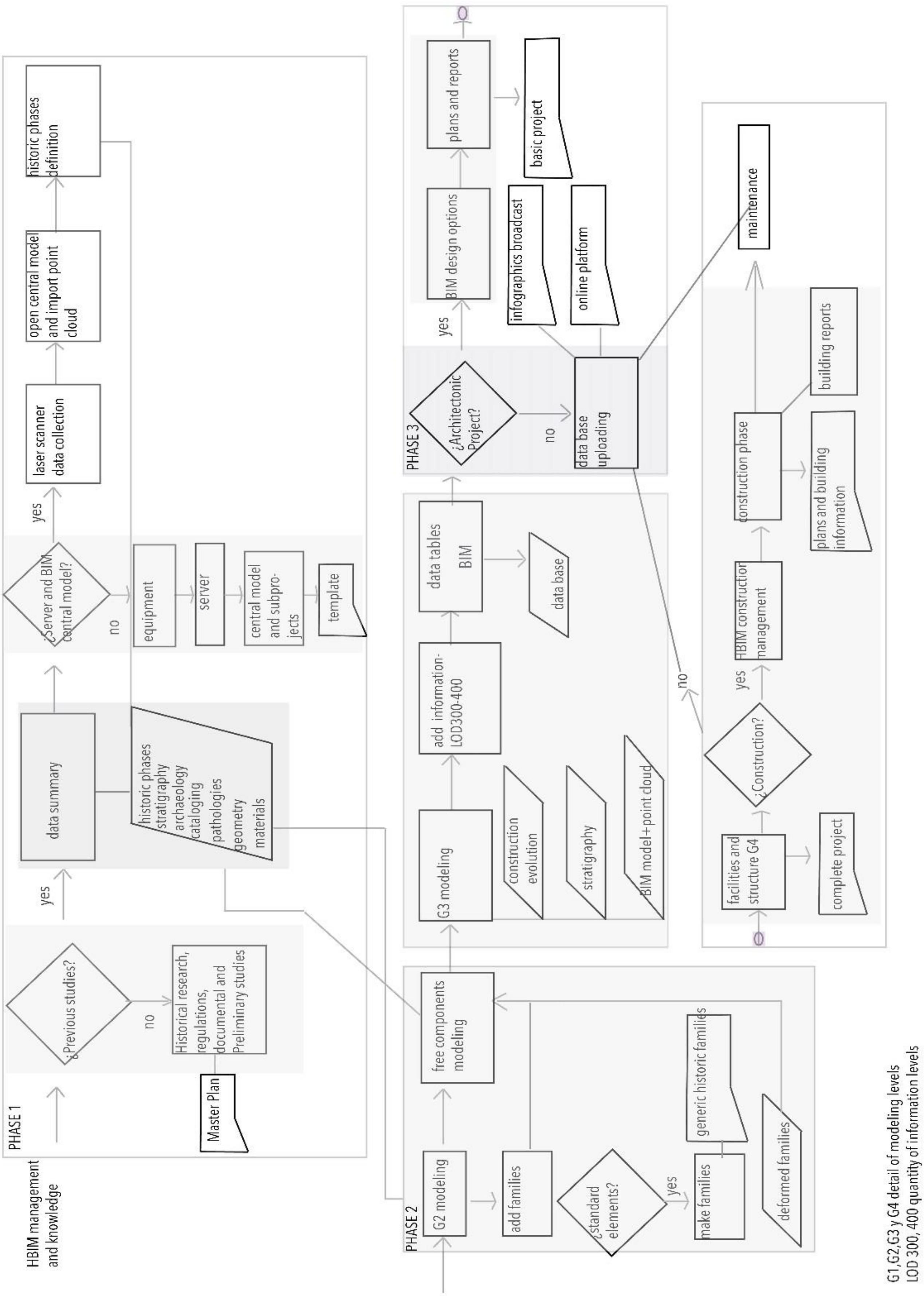
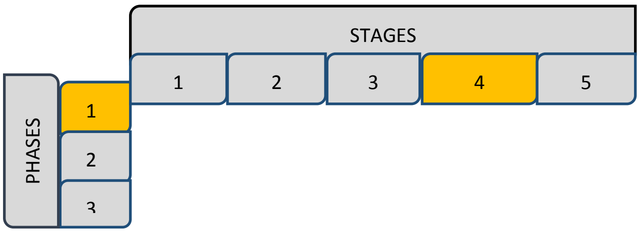


Figure 31. BIMlegacy protocol-1, 2016.

This section shows the process of design BIMlegacy protocol-1, which is the artefact created in phase 1 that was applied in Fixby Hall case study.

4.1.6 CASE STUDY 1: FIXBY HALL



BIMlegacy protocol-1 was applied to Fixby Hall case study to implement the solution/artefact in a real case and further improve it. This case study was developed during a doctoral research visit of four months at the University of Huddersfield. A report was presented to Fixby Hall stakeholders including partial results of this chapter of the doctoral thesis (Jordan *et al.*, 2017). This report was published in the repository of the University of Huddersfield, and it consists of the main text and two annexes (Jordan *et al.*, 2017). Figure 32 is an external view of Fixby Hall, in Huddersfield; the case study building.

Figure 32. Fixby Hall external view. Fixby Hall website, 2016.

4.1.6.1 Case study description and objectives

The specific objectives of the case study with Fixby Hall were: (1) to obtain information about the traditional work processes and stakeholders in the historical buildings to improve BIMlegacy protocol-1 (Figure 31); (2) to manage the historical buildings' life cycle with HBIM; (3) to make BIMlegacy protocol-1 more user-friendly; and (4) to validate it from its potential user's perspectives.

The data collected through the Fixby Hall case study was obtained from different companies and stakeholders involved with the building in the past and/or present. Those were: a Real Estate company, Huddersfield Golf Club (HGC), an architectural studio, an interior design company, a planning consultant company and a local construction company.

Fixby Hall benefited of BIMlegacy protocol having a helpful guidance for its future interventions and knowing the possible benefits of applying HBIM to this historical building. The main findings around Fixby Hall are described in section 4.1.6.3 including:

- History summary and Existing use of Fixby Hall
- Existing stakeholders involved in intervention projects at Fixby Hall
- Past refurbishment's approaches at Fixby Hall
- Difficulties identified in previous interventions at Fixby Hall
- Existing building information system at Fixby Hall
- BIM applied to Fixby Hall

The findings showed a prominent level of collaboration between stakeholders, ordered processes, and clear structures. The aspects that could be further developed include the lack of HBIM implementation and the lack of a central digital archive system in Fixby Hall. The conclusions of the case study demonstrated benefits in the possible BIMlegacy application to Fixby Hall and the useful HBIM approaches to this historical building's management.

4.1.6.2 Research process of Fixby Hall case study

The case study method (Yin, 2009) was used in this case study, and the data collection stages are described below (see Figure 33).

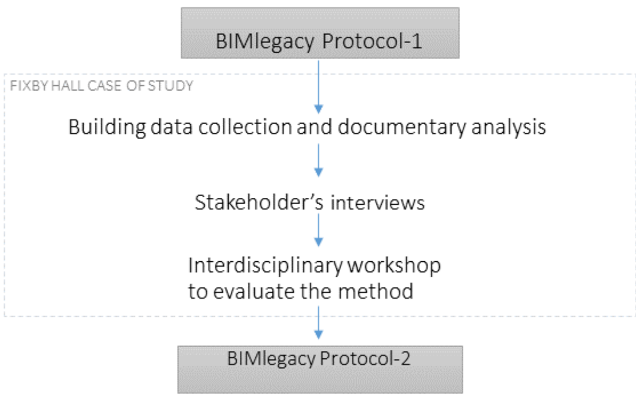


Figure 33. Main activities of the Fixby Hall Case study, 2016.

Firstly, data was collected consisting of a general comprehension of the organisation of the building, identification of the involved stakeholders, one site visit, a photographic report, and investigation of old architectural designs. This investigation also included the identification of relevant historic and architectural documents, personal archives of diverse stakeholders, and the study of the 125 anniversary book of HGC (Smith, 2016).

Secondly, seven one-hour semi-structured interviews were developed with: (a) the property, (b) the HGC President, (c) the HGC secretary, (d) the archivist, (e) the English

Heritage Outreach Manager, (f) the interior architect, and (g) the contractor, all involved in previous refurbishment projects in Fixby Hall.

The main questions that were asked follow:

- In case a refurbishment of Fixby Hall was needed, what type of procurement is likely to be adopted?
- In case a refurbishment of Fixby Hall was needed, what would be your involvement?
- Which data would you consider important to include in a BIM model?

In the next stage BIMlegacy Protocol-1 (Figure 31) was presented for evaluation during an interdisciplinary workshop with the main stakeholders involved in Fixby Hall. The stakeholders evaluated the protocol stages and activities. This workshop included the director of the Real State Company, the HGC President, the architect, the planning consultant, and a BIM consultant. The workshop has been transcribed and analysed with the scientific tool named NVivo. From this analysis, findings of Fixby Hall management, HBIM adoption, and BIMlegacy implementation were obtained.

This section presents the Fixby Hall findings, the conclusions of the case study, and the recommendations for Fixby Hall.

4.1.6.3 Fixby Hall findings

A set of semi-structured interviews, developed between October and November 2016, was performed with the following stakeholders related to Fixby Hall:

(A) The property: The Real State Company director, also a charted surveyor, 26 years of experience.

(B) HGC President: experienced in banking, hospitality and events management, 8 years of experience.

(C) HGC secretary: golf club basis management, 28 years of experience.

(D) Archivist: voluntary position, 12 years of experience as HGC archivist.

(E) English Heritage Outreach Manager: external consultant for the Real State Company, more than 10 years of experience.

(F) Interior architect: professional interior designer, more than 5 years of experience.

(G) Contractor specialised in plumbing and acclimatization: 15 years of experience.

The interviews had different questions depending on the interviewees' profile. These focused on the processes developed by the stakeholders, the relationships with other stakeholders, how information is archived, and the use of innovative technologies in their work, and included the following specific questions:

- Would you consider important to have an "as built" BIM model of Fixby Hall for further maintenance control?
- What kind of information do you think would be useful to have on a BIM model of Fixby Hall in order to support its maintenance and refurbishment?

- Would you be interested to contribute personally to the work of the design team through online BIM websites?

The main Fixby Hall historical building findings were:

(A) History summary and Existing use of Fixby Hall

Fixby Hall, listed building grade II, is owned by the Thornhill family since the 13th century when Sir Richard de Thornhill married Matilda of Fixby and it is thought that the Fixby Hall Estate was created (Smith, 2016). The main building is placed in a large Estate with partially wild woodland. The Estate also possesses other relevant buildings as the Orangery or the Stables (Faulhaber, 2010) Since 1808, the building has been occupied by Thornhill family members who have maintained it and done different refurbishments. Among these refurbishments, the building modernisation made in the middle 18th century which transformed it to its present Georgian style (1720-1740) stands out (Smith, 2016). Between 1808 and 1892, Fixby Hall was rented to several tenants like Richard Oaster, labours rights defender. Nowadays, Huddersfield Golf Club is the current tenant, and the letting and operating is left to the real states company Thornhill Estates Limited, directed by Edmund George William Thornhill, who owns the building.

The building and surrounding area have been rented to Huddersfield Golf Club since 1892. It is being used as a sportive and leisure club, and it has been used recently as an events venue. In conclusion, this heritage building achieves cultural and constructive qualities to potentially use in HBIM.

(B) Existing stakeholders involved in intervention projects at Fixby Hall

The responsibility of the historical building conservation, as part of the collective culture, lies not just with the architects and contractors but also the owners, tenants and people involved in the daily life use of the building. The restoration projects usually involve a complex social network and the decision making should be consensual. In previous Fixby Hall's interventions, different stakeholders have participated collaboratively in the conservation or renovation projects. Figure 34 represents the current map of stakeholders who were involved in Fixby Hall's management highlighting those related with maintenance and conservation.

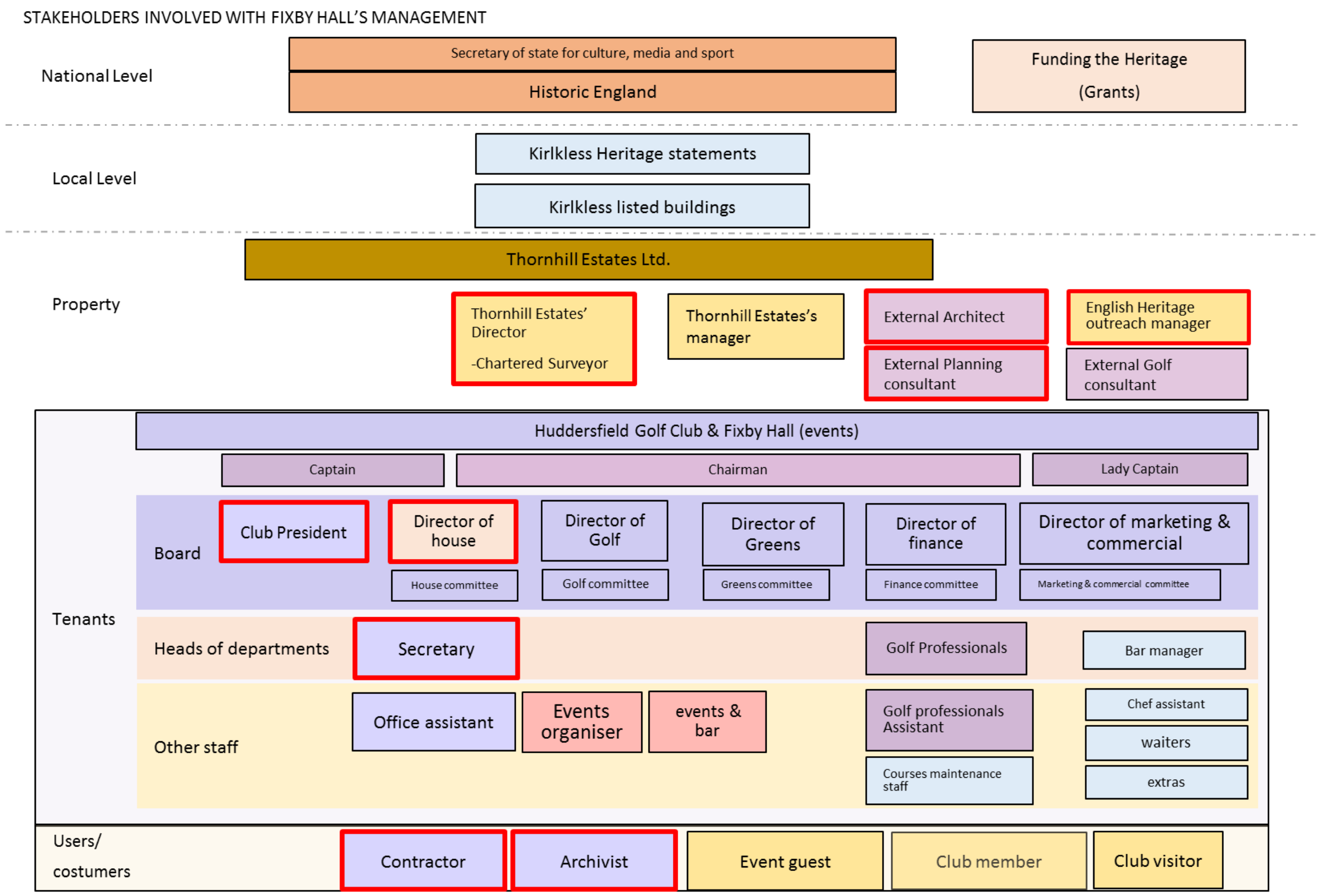


Figure 34. Fixby Hall's general stakeholder's structure. Highlighted in red are those with an implication in the building's maintenance and with this case study, according to the interviewees, 2016.

The **legislative frame** for Fixby Hall's refurbishments are Historic England at the national level and Kirklees City Planning department and Heritage department at the local level (Faulhaber, 2010).

A Real State Company, **the property**, manages and supervises the use and conservation of Fixby Hall. It owns different properties and the nature of its business is letting and operating owned or leased real estates. The company has a very close monitoring of its properties offering a continuous quality maintenance service (Interview with the property, 2016). The company's director and manager are involved in managing or supervising Fixby Hall's maintenance and conservation. Due to the long-time frame in which Fixby Hall has been rented to HGC, they have a very close relationship.

Sometimes, external consultants collaborate with the Real Estate Company. For instance, a golf consultant has helped in the golf sportive and business approach within Fixby Hall. Also, an English Heritage outreach manager is working on improving social engagement with Fixby Hall (English Heritage outreach manager's interview and Golf consultant's interview, 2016).

HGC, the **tenant** organisation, is led by the Chairman and, as a sport club. It has a Golf Captain and a Lady Captain who do not participate in managing refurbishments but in sport issues. The Board, HGC's main representative body, is composed by the Club President and the Directors of five departments: House, Golf, Greens, Finance, and Commercial and Marketing.

The **House Department** oversees the building's maintenance and conservation. It is composed by the Director and its committee, which is formed by five or six members of the club with maintenance knowledge and interest. They manage regular maintenance operations required by an old construction and major building renovations which are agreed upon with the Board and with the property (interview with HGC President and HGC Secretary, 2016).

HGC secretary manages the club formalities, communicates issues between different departments and if required, she manages any urgent maintenance problems. She also documents the regular and extraordinary HGC meetings, where the Board explains to the golf members not just the normal golf club concerns, but also the maintenance operations and refurbishments. The meetings have been documented since the building was used by HGC. Thus, these records are a large source of information.

The **archivist** of the Club studied and summarised this documentation creating the 125 anniversary book (Smith, 2016). It is a well-made compilation of the History of HGC (i.e. Golf Course, famous visitors, best golfers, and club memorabilia), the Thornhill Family, and illustrious events that happened in Fixby Hall.

A set of flowcharts were created representing the stakeholder's tasks during previous Fixby Hall refurbishments. During the interviews, initial and more generic flowcharts were presented to the interviewees to ensure accuracy published in the Annex of the Report of the case study (Jordan *et al.*, 2017).

As an example, the property flowchart is presented bellow on Figure 35. In the flowchart, the general tasks that the owner develops in his daily work are represented in intense orange. The maintenance and the intervention are the tasks of interest for this study, hence, they are surrounded by a blue dash line and are more detailed.

After the interviews, the flowcharts were updated according to the information provided by the interviewees. The final flowcharts of Fixby Hall stakeholders' tasks related with the building's maintenance and previous refurbishment are presented in annex 1 of the Report given to Fixby Hall stakeholders and published at the University of Huddersfield repository (Jordan *et al.*, 2017). As an example, the final flowchart from the owner's point of view is presented in Figure 35.

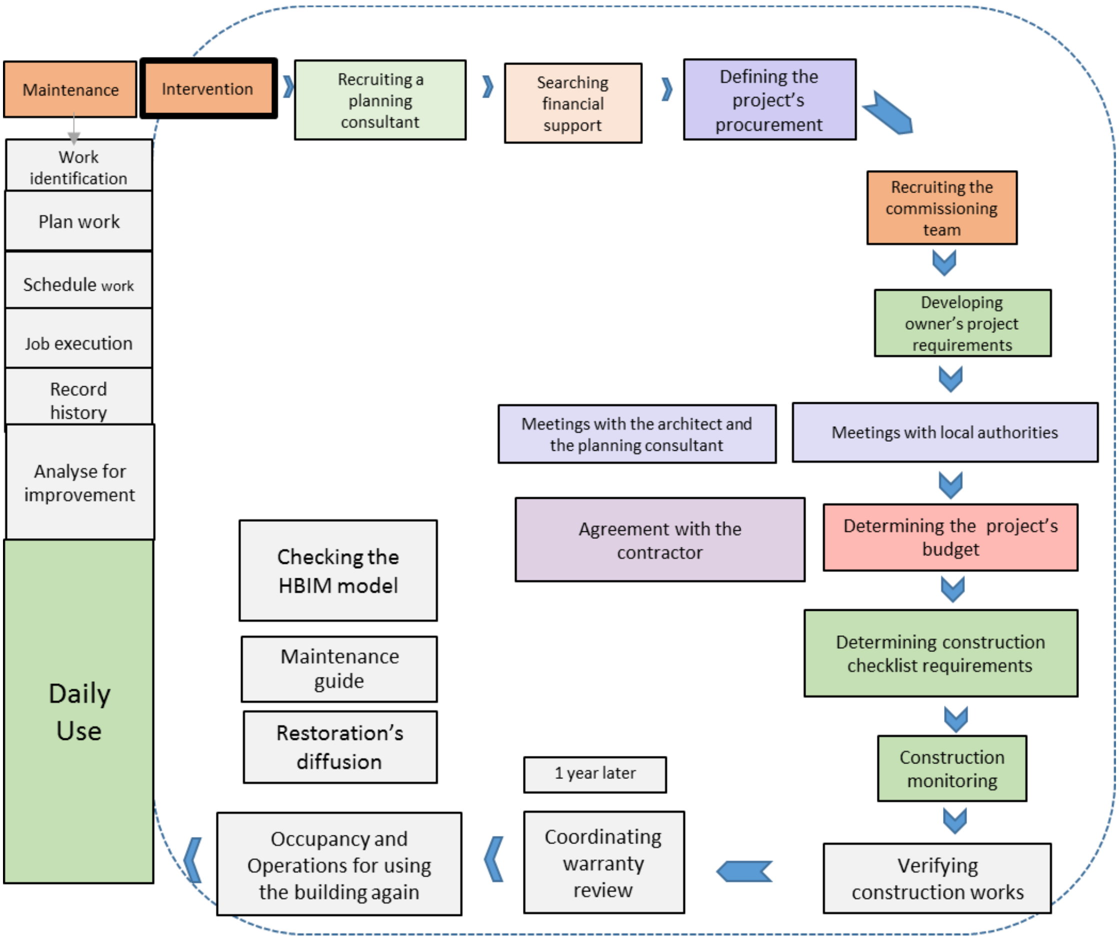


Figure 35. Final flowchart from the owner's point of view presenting the tasks related with the building maintenance and refurbishment. It was developed with the data provided by the owner in the interview, 2016.

(C) Past refurbishments approach at Fixby Hall

Huddersfield Golf Club is in charge of the maintenance and conservation of the building, they have done several repairs and refurbishments, both in the house and in the golf course (HGC President and Secretary).

When a major refurbishment is needed, the Director of House and his counselling committee establish the refurbishment requirements, after an informal members' consultation and a discussion with the Real Estate Company that owns the building. Following, the Director of House presents the project brief to the Board, and if they give their approval, the project is commissioned to an architect, who usually is also a Club member. The Club members are informed about the refurbishment in a regular club meeting. Once the architect's design is given planning approval, it is sent to three different contractors to generate quotations. Finally, the House committee, together with the Board, decide which contractor is the most appropriate (interviews with HGC President and Secretary).

For minor interventions, which are contemplated in the annual budget of the House Department, the Director of House can directly go ahead with the project without formally addressing it with the Board. The contractor's economical quotation is supervised by the

Director of Finances and the refurbishment is informed to the Club members in its regular meeting.

The most relevant recent interventions in Fixby Hall have been: in 2003, consent for internal alterations to form an entrance lobby and a reception office submitted by Kirklees Planning and development department, (Faulhaber, 2010); and in 2014, intervention in the locker room and the restroom designed by the interior architect and constructed by F and R Mallinson Ltd (interviews with HGC President, HGC Secretary and contractor).During the construction work of these interventions, the building was not evacuated, so the construction work needed to be coordinated with the regular life at Fixby Hall. This coordination labour was mainly done by the Secretary or her office assistant (interview with HGC Secretary).

These previous interventions in Fixby Hall had been leaded by the House Department (interview with HGC President). The designers and the contractors were from diverse companies. Concretely, in the locker room refurbishment, all stakeholders involved were members of Fixby Hall: the interior architect and the HGC President are members of the House committee, and the contractor is a club member. Thus, there were frequent coordination meetings in a very familiar environment, which propitiated the successful results of the project (interview with HGC President). The flowchart with the tasks developed by the Fixby Hall stakeholders is presented below (Figure 36).

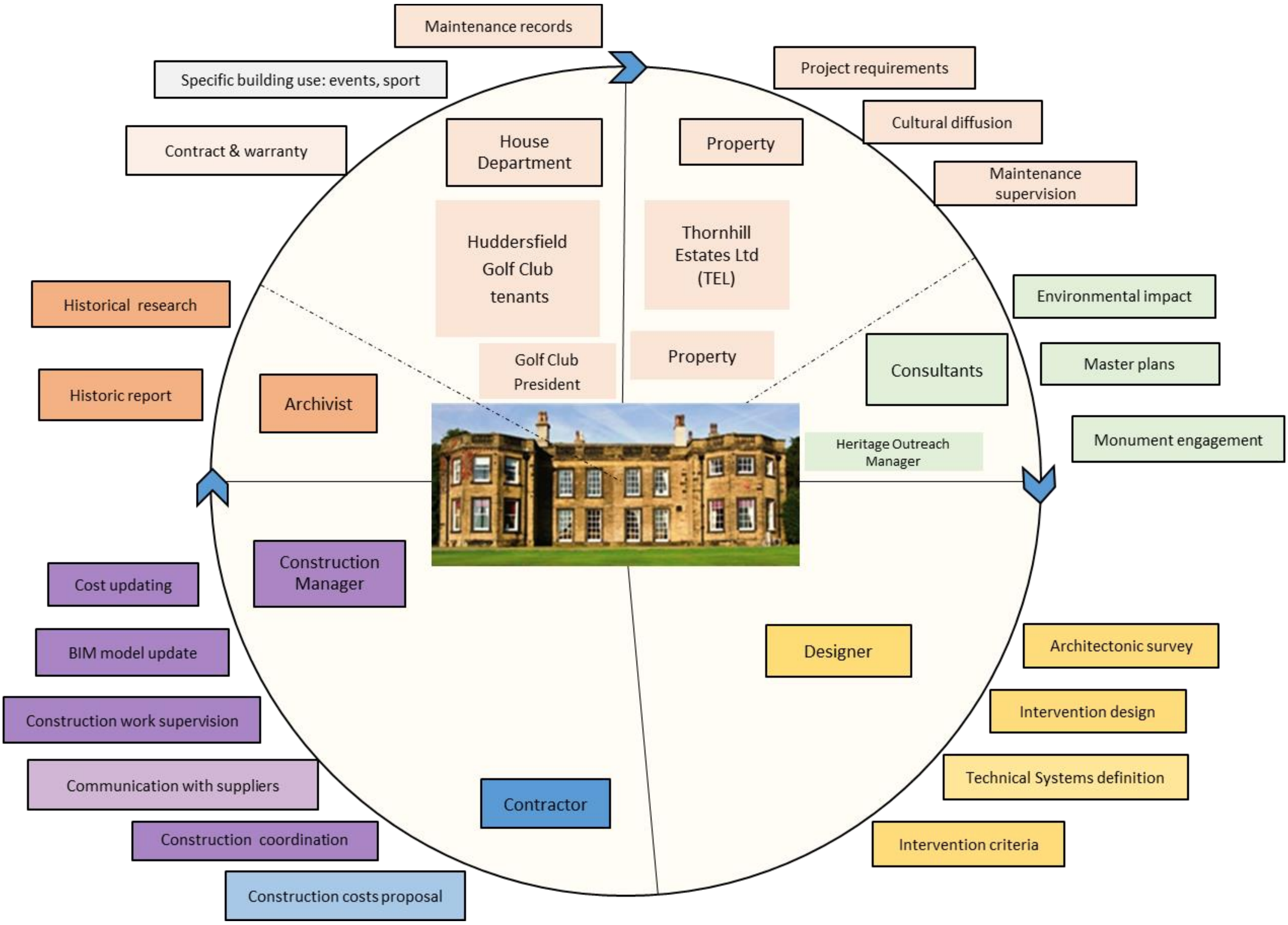


Figure 36. Tasks developed by the Fixby Hall stakeholders, 2016.

(D) <u>Existing building information system at Fixby Hall</u>

The information about previous interventions in Fixby Hall and its management are separately archived by the different companies involved. Each of the stakeholder's archives different types of information in different places, as it is described below:

The property, Thornhill Estates Ltd (TEL), has their own digital storage archiving the historical and part of the architectonical information of their various properties. This system is thought to modernise into a sophisticated online collaborative database that can archive ordered data of all the buildings that the company owns (interview with the property).

The Golf Club has its own archive with physical folders, which contain the historical records of the Club meetings (interviews with HGC archivist). Recently, the archivist of the Club wrote the book "Huddersfield Golf Club 125 years at Fixby" doing an interesting compilation of the Golf Club paper records. The information of the building management was mainly archived in the Golf Club archive (Smith, 2016).

F and R Mallinson Ltd, the construction company, works with a digital folder system in which every building they work on is archived, including the e-mailing system and the specific application for managing repairs. They have the technical and constructive data (interview with the contractor).

The architects at Enjoy Design Ltd and the designers involved in the research archived the information digitally and with increasing degrees of online collaboration. They possess the design and technical documentation (interview with the architect).

(E) Difficulties identified in previous interventions at Fixby Hall

Previous interventions in Fixby Hall were successful in terms of cost and time. There was an elevated level of collaboration between the different companies' stakeholders, ordered processes and clear department's structure. However, issues that different interviewees pointed out were:

- Lack of preventive maintenance in the building.
- The building information was separately archived by the different stakeholder who participated in the projects.
- High time demanded for the House Director and his committee (interview with HGC President).
- Historic buildings have a series of unknown elements and additional works that may need to be resolved after the contract has commenced, because of the frequent issues founded on site (interview with the contractor).

In the annexe 1 of the report published in the University of Huddersfield repository (Jordan *et al.*, 2017), are shown the tasks that every Fixby Hall's stakeholder develops within an HBIM project.

(F) HBIM applied to Fixby Hall

There had not been a BIM intervention in Fixby Hall due to the last refurbishment being done before this technology was available. However, different stakeholders had declared that the system could be very helpful for future interventions in the building.

BIMlegacy Protocol-1 can gather the historical evolution of Fixby Hall facilitating the managing and visualization of future interventions. Fixby Hall has accumulated diverse interventions in its construction items as well as in its surroundings and courses. The application of HBIM could unify and represent the whole constructive-historic evolution in one single file.

A good maintenance and service plan for existing buildings, such as Fixby Hall, is very important for the building users. Therefore, having clear and complete maintenance information in an HBIM model using BIMlegacy protocol is very useful.

The 'as built' HBIM model would be very useful for contractors, architects and owner because it can control the facility management, explore better sustainability and energy efficient systems, control the degradation of materials and furniture (i.e. cracks, humidity), manage the tenancy and occupancy, and control the furniture inventory of historic buildings. This aspect could be useful to manage not just Fixby Hall but also similar buildings. It is recommended to apply HBIM progressively and start using it on a small building, such as it is the Orangery, as a pilot case.

The community engagement with historical buildings such as Fixby Hall is very important to raise public awareness on the cultural value of our heritage and the need of heritage resources and education. HBIM models can be used as source of visual information to engage and explain the cultural value of Fixby Hall to the community (interview with the Heritage Outreach Manager).

The BIMlegacy Protocol should be simple and friendly so all the stakeholders, technical and not technical, can understand and use it (interviews with the property and the contractor). Thus, it is recommended to progressively adapt Fixby Hall to HBIM systems.

The valuable history of Fixby Hall as well as the history of its historic characters could be loaded in a historical online database linked with the HBIM model. The identification of the community with their culture becomes stronger when having a physical building or a physical 3D virtual building that makes them recreate better the historical facts.

4.1.6.4 Conclusions and recommendations

<u>Conclusions of Fixby Hall case study</u>

- Fixby Hall is a well-managed historic building regarding maintenance and refurbishments. However, it has not yet adopted more productive systems such as the BIM.
- The departments and structures of Fixby Hall are well organised and the stakeholders have a good relationship with frequent meetings.
- The building's documentation is spread out between the different stakeholders. There are diverse archives where there are various kinds of documentations related to the building (a.e. HGC archive, Thornhill Estates Ltd.'s computer system, FandR Mallinson Ltd company digital archive system).
- The existing drawings of the building (i.e. floor plans, elevations and sections) were generated with traditional architectonic data collection. Even though it is of high quality, nowadays there are better systems which could improve the accuracy of the architectonic survey.
- BIMlegacy protocol helped non-technical stakeholders to be active within the HBIM process.
- BIMlegacy protocol helped the distribution of information or the disconnection between the works of heritage stakeholders improving the project quality.
- BIMlegacy protocol contributed within the cultural diffusion of Fixby Hall in the local community.

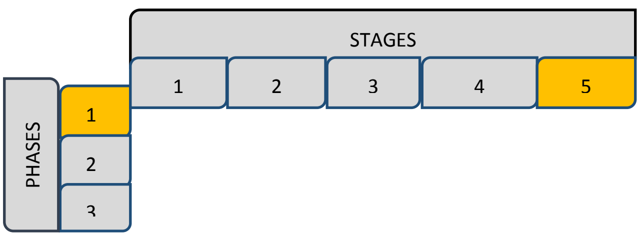
<u>Recommendations for Fixby Hall</u>

- It would be very useful to have an "as built" HBIM model for Fixby Hall because it would concentrate all the information related with maintenance, MandE conditions and the building's degradation. Consequently, it would be very easy and fast for the House Department to find specific documentation.

- An architectonic-constructive HBIM model with all the historical phases and changes that the building has had will be very useful for future refurbishments. This 3D HBIM model could also have the historical information of the building linked with the architectonic elements.
- To generate a point cloud with photogrammetric architectonic survey of the building would procure an accurate document to start any kind of BIM model.
- Preventive maintenance in Fixby Hall would be a good practice since it is a considerable large ancient building. Preventive maintenance, with the right BIM documentation, would result in long-term affordable preventive maintenance rather than corrective maintenance, which means to do repairs just when something breaks and in general is costlier.
- It would be beneficial to implement the protocol BIMlegacy-1 in the next Fixby Hall's refurbishment to manage the design and construction phases. This HBIM model would be an excellent documentation that could be utilised in further interventions in Fixby Hall as well as in possible interior design projects and furniture re-distributions, enabling 3D simulations.
- In future refurbishments, it would be beneficial to include all stakeholders from the inception of the architectural design.
- The HBIM models are very visual to explain construction actions to a great public. Thus, Department of House could use them to justify any construction action to the club members.
- A unified digital infrastructure is recommended for Fixby Hall to order the documentation.

In conclusion, HBIM and BIMlegacy protocol-1 will help Fixby Hall to be at the forefront of historic buildings management trends by unifying a variety of information and enhancing its historical values. An HBIM Implementation Plan is the required document to achieve this proposal and continue with this research. The experience gained in Fixby Hall case study assisted to improve BIMlegacy protocol by identifying further stakeholders and linking traditional processes with HBIM processes.

4.1.7 WORKSHOP TO EVALUATE BIMLEGACY PROTOCOL-1



Different stakeholders related to Fixby Hall were invited to a multidisciplinary workshop to contribute with their necessities and requirements within the innovative BIMlegacy protocol-1 for managing historical buildings. The workshop was performed with historic architecture stakeholders and BIM stakeholders in order to present and validate the designed BIMlegacy protocol-1 in Figure 31. The purpose was to discuss the validity and the possible improvements of the designed BIMlegacy protocol-1 with potential users. This one hour and a half workshop was held at Huddersfield University, Queen Street Building, on December 14th of 2016, and the participants were:

(A) Fixby Hall property: The Real State Company director who is also a charted surveyor, 26 years of experience.
(B) The architect: who works with BIM and HBIM, has more than 20 years of experience.
(C) The planning consultant: experienced in heritage buildings, more than 20 years of experience.
(D) Huddersfield Golf Club President: experienced in banking, hospitality and events management, 8 years of experience.
(E) BIM consultant: with knowledge in Lean Construction and in BIM implementation, 4 years of experience.

The workshop started with a concise explanation of what the HBIM is. Then, the designed BIMlegacy protocol was explained presenting its eight steps. Then, six specific questions were asked, including:

- After seeing BIMlegacy protocol, are some steps involving the intervention of the historical buildings missing? Are some stakeholders missing?
- Is the model easy to use?
- Who would document the HBIM during construction and maintenance?

The participants were very active creating an interesting debate giving examples from their own experience and discussing workable solutions to achieve potential problems.

The workshop has been transcribed and analysed with the scientific tool named NVivo and the information was analysed identifying the protocol's possible issues and solutions.

Difficulties for small restoration companies to adapt to BIMlegacy protocol-1

Even some large construction companies use BIM, but small companies working in historical buildings have generally not enough resources to invest in HBIM. The workshop's participants described that the refurbishments where they have been working were in general not fully performed with HBIM.

Thus, BIMlegacy protocol-1 could not be fully apply in small restoration companies. Though, they could progressively implement BIMlegacy protocol with different levels of maturity, depending on the company's resources and the clients' needs.

UK legislative frame is perceived to slow BIM adoption

The participants agreed that there are several bodies in the United Kingdom (UK) that need to be consulted since they can object the building intervention: 0) international, 1) national, 2) local, and 3) civic societies.

According to the planning consultant's lifelong experience managing tender documentation, these institutions will have a slow BIM adoption because they have neither the human or economic resources to push this process.

UK legislative frame's probable slow adoption will condition BIMlegacy protocol's complete use.

BIMlegacy Protocol-1 needs to add the structural study as a complement for the laser scanner

The quality of the BIM model for historical buildings would vary depending on the survey and the starting information. The laser scanner technique saves time when doing the building survey providing a great accuracy on measurements.

During the workshop, some participants explained that even the point cloud technology is thought as the best way to document the existing condition of a building; it has limitations as to what is inside the fabrics due to the fact that this technology is only able to record the exterior side of the walls.

Consequently, the structural studio to analyse the wall's cohesion and structures' strength is still required and needs to be added to the BIMlegacy protocol-1. The point cloud would just be the framework for a BIM model, on agreeing with the BIM consultant.

BIMlegacy Protocol-1 needs to define who documents the model with the construction and maintenance data

The property representatives argued that they would not have the time or knowledge to update a hypothetic HBIM model. The technical stakeholders (i.e. architect, BIM consultant) exposed that updating the BIM model with constructive and maintenance information would increase the project's budget since it is an extra service.

The consensus opinion was that BIMlegacy protocol-1 needs to progressively adapt to higher levels of HBIM documentation. Since the contractor or the property may own the model, then a technician from the contractor company would document the model during construction and/or maintenance.

BIMlegacy Protocol-1 requires stakeholders with BIM skills

Nowadays, just some architects and engineers use BIM, as well as some big construction companies. Consequently, HBIM projects cannot yet achieve a high level of maturity because of the poor BIM knowledge of mainly the non-designer's stakeholders, hence so the productivity is not as high as it could be.

According to the participants, the historical building's stakeholders are: owner, planning consultant, chartered surveyor, historian, archaeologist, monument manager, planning officer, architect, engineers, contractor, suppliers, construction manager, construction workers, and restorer. Just some of these stakeholders have BIM knowledge, thus, BIMlegacy protocol-1 needs to include BIM education for the non-designer stakeholders.

On this line, "HBIM for the property" needs to be as much user-friendly as possible since property agents have no previous technical knowledge.

Therefore, an HBIM platform should be added to the BIMlegacy protocol-1. Online BIM platforms, as A360 or BIM Legacy were agreed to be very useful to communicate among different stakeholders during the project because they were thought to be very visual and easy to use.

The construction workers are key stakeholders who should adapt to BIM because they are the last link in the building process. In order to reduce site mistakes, complementary technologies linked to BIM, such as 3D glasses, should be added to the HBIM Method.

BIMlegacy Protocol-1 needs to define the HBIM model's levels of maturity

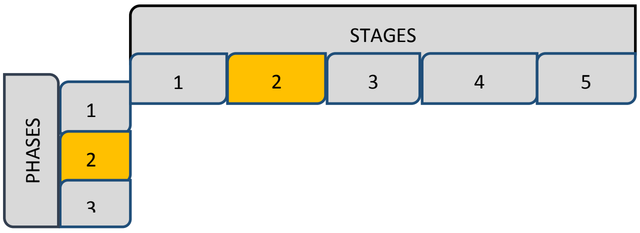
The participants thought that the level of maturity, how detailed is the modelling and how much information the HBIM model contains, must be defined in the BIMlegacy Protocol.

The over working and the duplication of work cause economic loses; consequently, defining tasks in the initial strategy is essential. Thus, different levels of maturity need to be defined depending on the different project's purpose and property engagement. A conventional historic building property cannot afford the costs of a maintenance HBIM model. However, in 5 to 10 years' time the levels of maturity of the models would increase.

4.2 PHASE 2

Phase 2 started defining the objectives after the experience achieved in Fixby Hall case study and the evaluation of BIMlegacy protocol-1 in the workshop with Fixby Hall stakeholders. The specific objectives of phase 2 of the investigation were:

- Understand traditional heritage architecture processes.
- Simplify BIMlegacy protocol-1.
- Extend the method to the entire life-cycle.
- Create an online HBIM platform to enable information sharing.



4.2.1 CHANGES PERFORMED BETWEEN BIMLEGACY PROTOCOL VERSION 1 AND 2

Ones the objectives were stated, the protocol was redesigned to incorporate all the knowledge achieved in phase 1 of the investigation. The design of BIMlegacy protocol-2 (Figure 42) took into consideration the analysis of the workshop conclusions.

The main issues detected in BIMlegacy protocol-1 include:

- Difficulties for small restoration companies to adapt to the BIMlegacy protocol-1.
- The workspace or online platform for heritage stakeholders was not created in BIMlegacy protocol-1.
- UK legislative frame is perceived to slow BIM adoption and any HBIM protocol.
- BIMlegacy protocol-1 needs to add the structural study as a complement for the laser scanner
- BIMlegacy protocol-1 needs to define who documents the model with the construction and maintenance data.
- BIMlegacy protocol-1 requires stakeholders with BIM skills.
- BIMlegacy protocol-1 needs to define the HBIM model's levels of maturity.

Changes performed between BIMlegacy protocol version 1 and 2

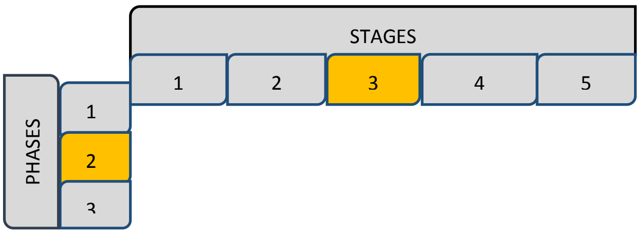
BIMlegacy protocol-1 was changed to achieve all the issues detected in phase 1 of the investigation.

- Protocol BIMlegacy-1 should cover all the life-cycle of the building to achieve successful results. It should not be focused just in the technical point of view, but in the social and processual too.
- The processes used traditionally in the refurbishments, such as the initial structure survey or the client brief, should be integrated in BIMlegacy protocol-1.
- Simplicity and clarity are key elements in the success of the BIMlegacy protocol-1. The stakeholders have diverse backgrounds and limited time to understand the

protocol. Evident and revelling graphics, as well as simple vocabulary, help the participants to understand the concepts.

- BIMlegacy protocol-1 should be adaptive to the project resources and scale. Factors as the kind of procurement, the project leadership, and the property of the HBIM model should be defined to adapt the project degree of HBIM adoption.
- The levels of maturity in the HBIM models should be adapted to the aims, scale, and human and economic resources of the historic projects.
- All historic architecture's stakeholders must be taken into account in the BIMlegacy protocol-1, including the planning consultant, the heritage outreach manager, the quantity surveyor, the property, the building manager, the restorer and the archaeologist.
- BIM education should be provided specifically for property and building managers. The property and building's managers should be active stakeholders, which means that they must understand methods and models.
- The relationship between HBIM stakeholders will improve when using online BIM workspaces thus, an online platform was created to complement the protocol. Tools such as A360 generate the creative conversations that are needed, especially for the first periods of design. To have an online platform would facilitate for all the consultants to see each other's work; e.g. the legal documents, and the technical drawings, the construction reports.

4.2.2 BIMLEGACY PROTOCOL-2: DESIGN PROCESS



The summary of the protocol's findings indicated the necessity to simplify the protocol, increase its scope to include the whole life-cycle of the buildings, create an online platform, and make it more flexible to different projects' scales and resources. Various tree diagrams were created in order to contemplate the list of changes in the new version of the protocol. These diagrams were mainly work flowcharts used to order ideas Figure 37, Figure 40, Figure 73, Figure 74, and Figure 41, presented below.

Figure 37 contains the processes within the design time, diamonds represent decision making, and rectangles represent processes or stages within the design time. The colours represent different stakeholders, for example, green is architect and orange is project manager.

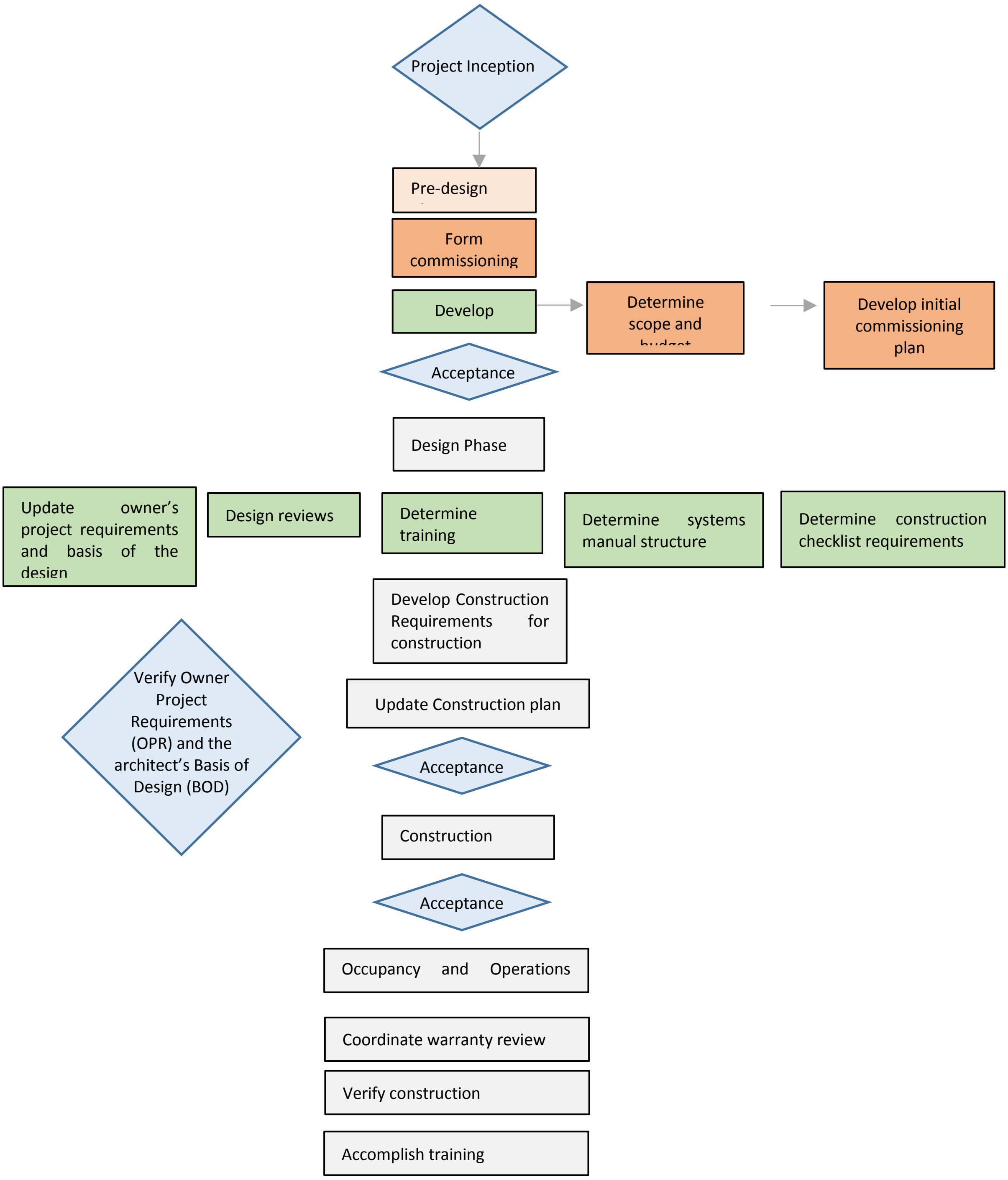


Figure 37. Design flowchart created from BIMlegacy protocol-1 to develop version 2, 2017.

The heritage traditional processes discovered within Fixby Hall case study were added to the protocol, ordered and connected according to the stakeholders' interviews and the workshop results (Figure 38). It represents the processes obtained in Fixby Hall case study, it means, what is the current use of the building and the evaluation of if it. Heritage buildings need to be maintained and they need to have a real use, otherwise they end up without maintenance and with the risk of becoming a ruin. Then, in case a refurbishment is required, it will be necessary to investigate if the building is catalogued and then to search for financial support. The architectonic survey of the current state of the building with laser scanner and the HBIM modelling is the next step of the process. The HBIM model entails the registration and the documentation of the model. The next question of the diagram, Figure 38, is the intervention design (preservation, restoration, or refurbishment) and all the sub processes that this process entails. Then, the clash detection of all the disciplines of the model, and after that the restoration or constructions works, follow. Finally, the maintenance phase in HBIM ends the diagram.

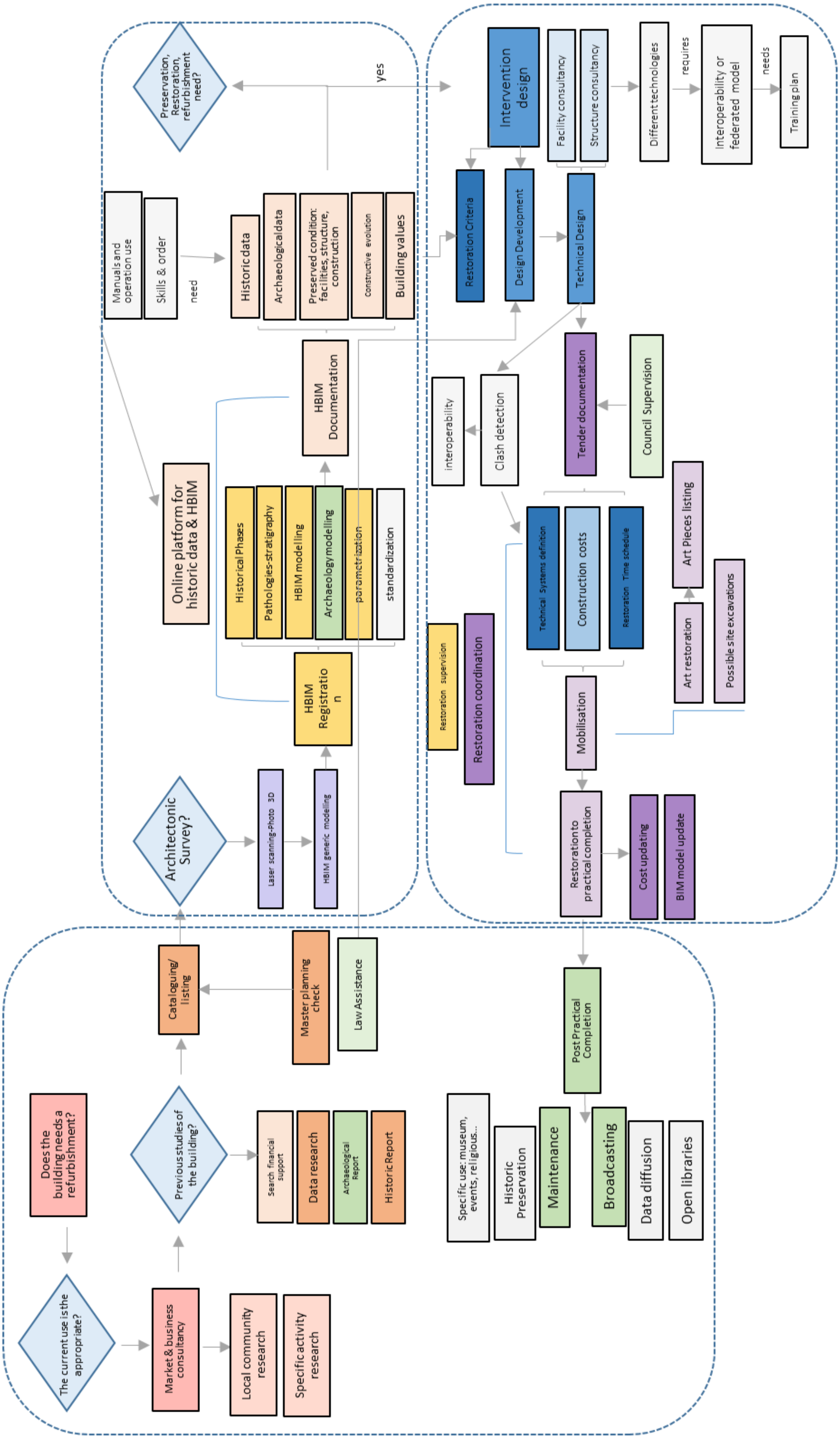


Figure 38. BIMlegacy protocol connecting heritage traditional processes, 2017.

The stages of the life-cycle of heritage buildings were synthesised in a circular diagram since a heritage building can achieve multiple interventions during its life (Figure 39). Thus, it was required to change the protocol structure into a circular type diagram.

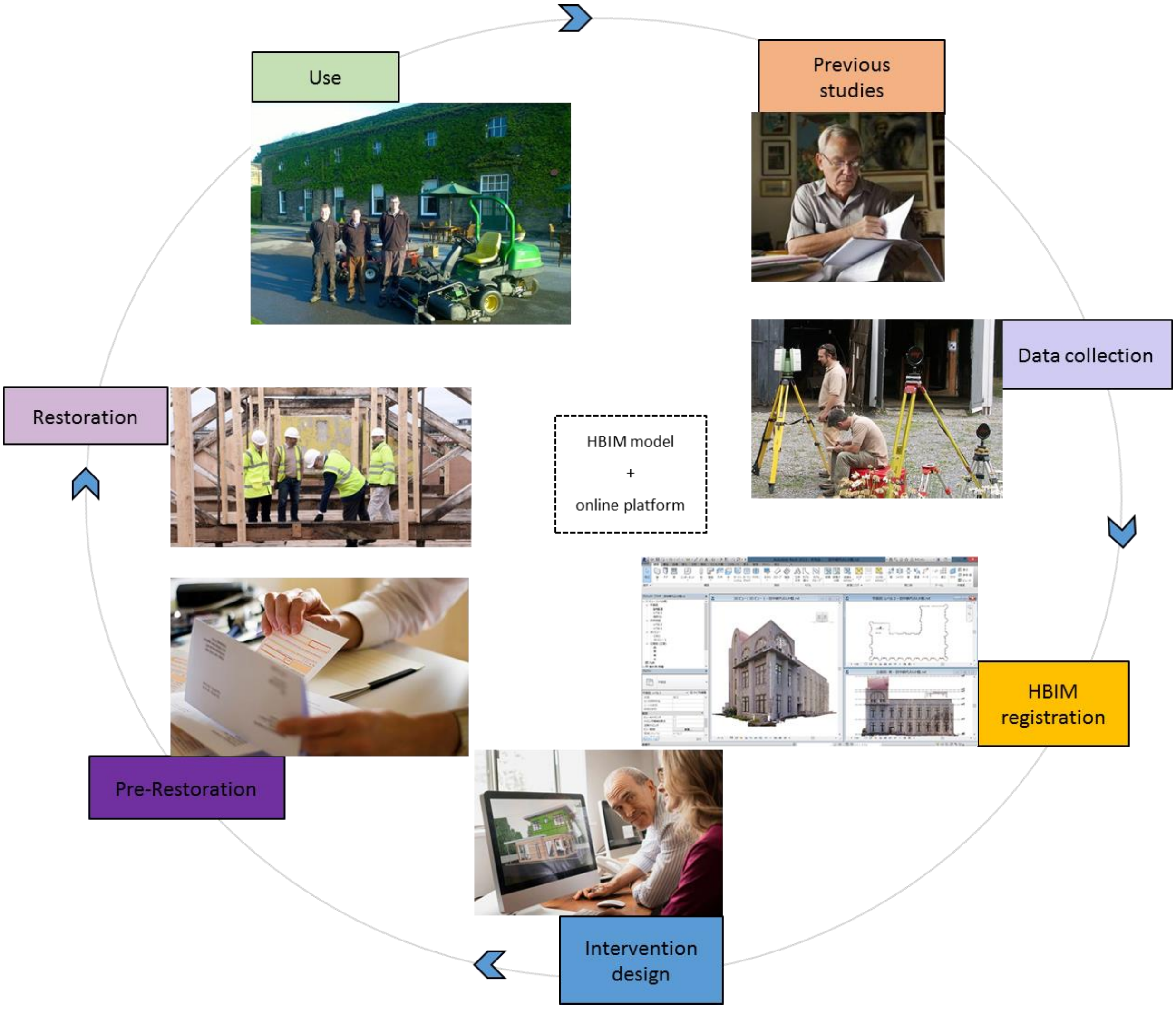


Figure 39. Circular diagram to contemplate all the life cycle of heritage buildings, 2017.

To extend the protocol to all the life-cycle of the building including the maintenance and use phases, the Council on Training in Architectural Conservation (COTAC) principles were taken into account creating a diagram that orders these principles in a circle and relates them with the steps of the life-cycle (Maxwell, 2014), Figure 40.

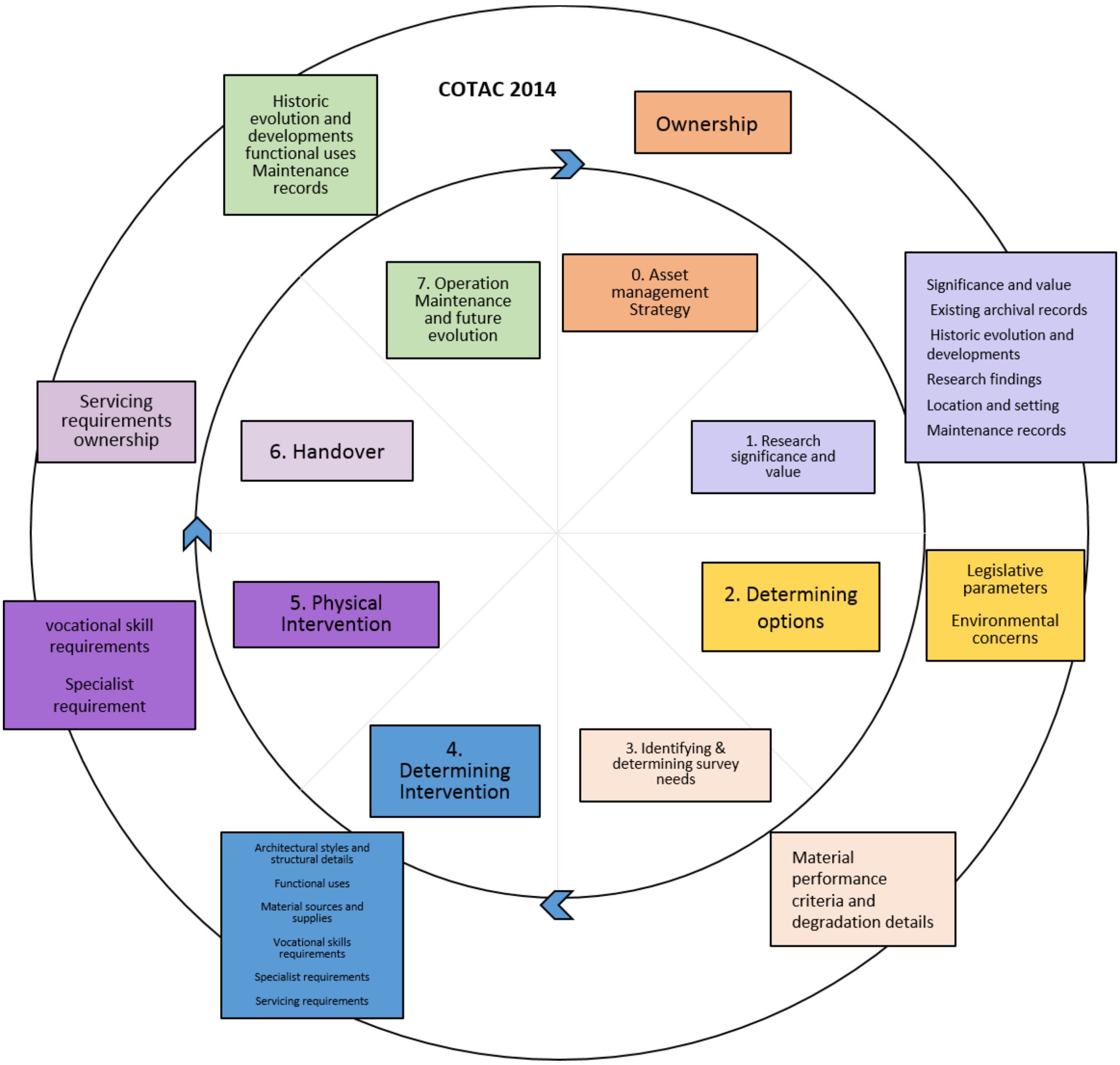


Figure 40. Diagram to order processes related with COTAC, 2014

Another objective was to have a platform were all heritage stakeholders could work together, share information in real time and synchronise its work. Thus, a flowchart to order these necessities was created, Figure 41, and indicating the kind of platform required in each step of the heritage building life-cycle.

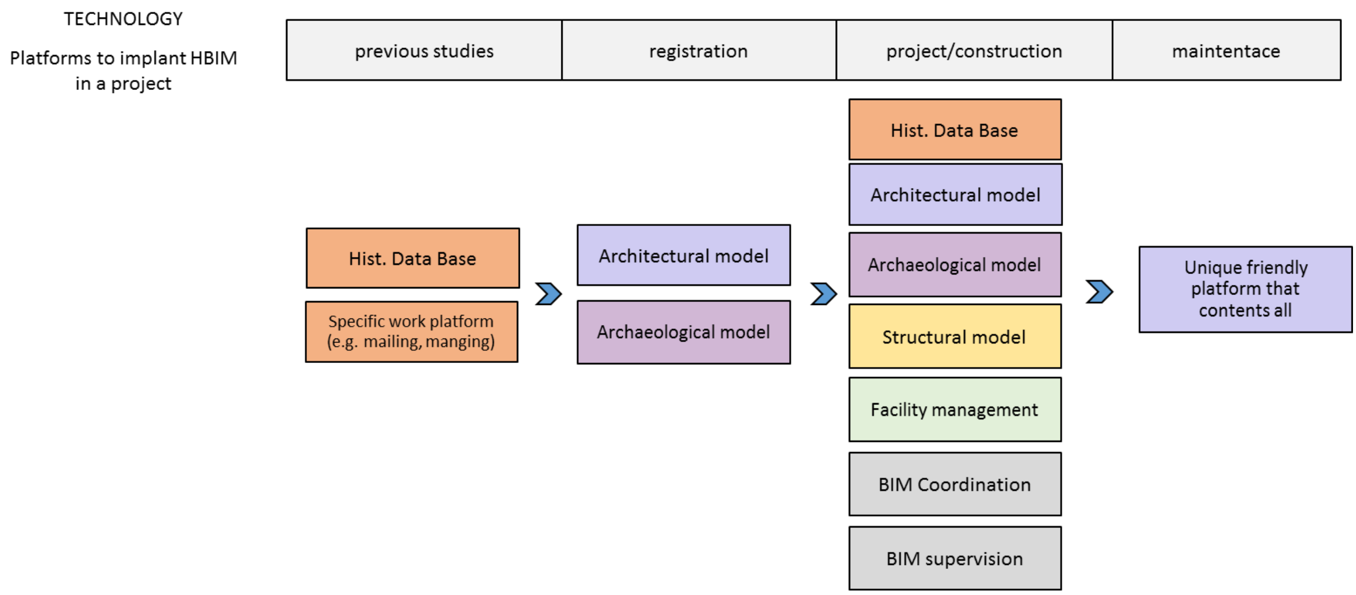


Figure 41. Workflow representing the platforms to implement HBIM, 2017.

BIMlegacy protocol-2, was designed overlapping flowcharts with affinity and tree structures techniques using all the Fixby Hall case study and workshop findings. The protocol needed to be simple according to the workshop conclusion, so that, BIMlegacy protocol-2 was simplified and the graphics used were also transformed to appeal as user-friendly as possible, Figure 42.

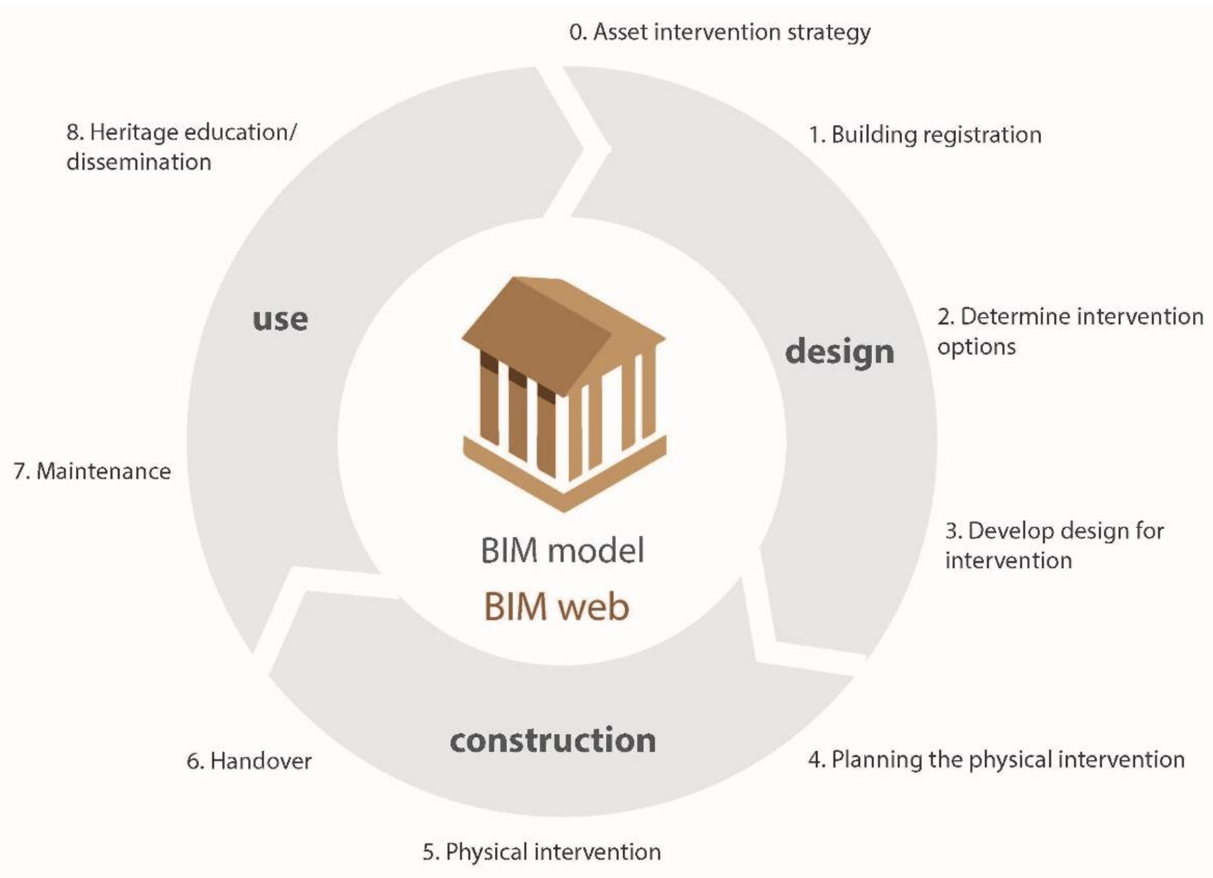
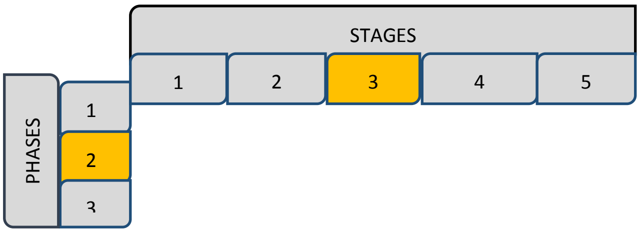


Figure 42. BIMlegacy protocol-2. Presented in the workshop for its validation with potential users, 2017.

In conclusion, all the information collected through Fixby Hall case study participants who were professionals working on heritage buildings and BIM environments was extremely interesting for the development of BIMlegacy protocol's version two. In phase 2 of the investigation two artefacts were created the BIMlegacy protocol-2, and BIMlegacy platform, as a consequence of the necessity to create a Common Data Environment (CDE) to share information between heritage stakeholders.

4.2.3 BIMLEGACY PLATFORM



As it is mentioned in the literature, there is a need for a more collaborative system in heritage projects (Zhao *et al.*, 2015); Combalía-Solís and Jiménez Cuenca, 1997). The results of the workshop in Huddersfield pointed out that BIMlegacy protocol required a platform to achieve a heritage project in practice. These facts have encouraged the creation of BIMlegacy platform.

This platform has been developed with the support of HAR2013-41614-R project "Design of a Database, Management Model for the Information and Knowledge of Architectural Heritage" (García Valldecabres et al., 2016). This platform has been used to develop the practical research of this doctoral thesis as a complement to the BIMlegacy protocol. The results of this project are under process of publishing in the Scientific Journal Automation in Construction. In this research participated Mr. Rubén March Oliver, Ms. Elena Salvador García, and Ms. Isabel Jordán Palomar. The specific contribution of this doctoral thesis within the designing BIMlegacy platform was as 3 years involved in the project as BIM manager, already explained in section 3.3.2.

BIMlegacy is an online prototype platform to manage heritage projects where technical and non-technical stakeholders can synchronise data and work effectively together. The information comes from the 3D HBIM models and the work website that has been designed as a documental database. Thus, the non-technical stakeholders can participate in HBIM without specific 3D BIM modelling knowledge. BIMlegacy connects the innovative HBIM methodology with the traditional registration tools since an exhaustive study of historic databases was previously performed.

BIMlegacy entails a CDE for heritage architecture sector unifying heritage architecture information. The platform is composed of a work website, a heritage diffusion website, a Revit plug in, and a WAN server. Revit was chosen as BIM modelling software because of its open programming core, its database structure, and its good interoperability.

Cultural diffusion is crucial for the preservation of heritage buildings. As BIMlegacy also has also a free-to access website to consult information on the registered monuments for cultural divulgation. It was designed to be both a work platform and a diffusion tool to bring the cultural legacy to the society.

The historic-artistic data base of the **web platform** is systematic and ordered, an essential requirement due to the large quantity of information that should be held within it. It is very important to facilitate researchers' access to the museum and archive documents.

BIMlegacy prototype has been developed in Spanish language and it is currently located in a LAN server granted by the Universitat Politècnica of València. It was designed to reduce the latency as much as possible to facilitate an agile synchronisation of information.

4.2.3.1 Platform architecture

The elements connecting the different databases of the system, represented in Figure 43, are:

- A plug-in that consist on a Software Developing Kit (SDK) Application Programming Interface (API) for Revit. This plug-in retrieves the needed information from the Revit model and consumes WebApi to synchronise the data of the Structured Query Language (SQL) server's data with the Revit file data.
- A WebApi. This is an applications programming interface published on the server web. The plug-in connects this WebApi to interchange information. The WebApi is independent from the plug-in and other types of applications, for example, a mobile application could also consume it.
- The Revit Core is a Dynamic Link Library (DLL) library packages responsible for managing the business layer and the data access.
- A database SQLServer is based on a relational model allowing working in a client-server mode. It storages information in the cloud, supports millions of registrations and does not have users' limitations.
- A web portal, which facilitates data insertion, edition and consultation in any graphical location. It would be oriented to non-technical stakeholders who do not usually work with BIM (a.e. historian, art historian, monument manager) and to external visitors.

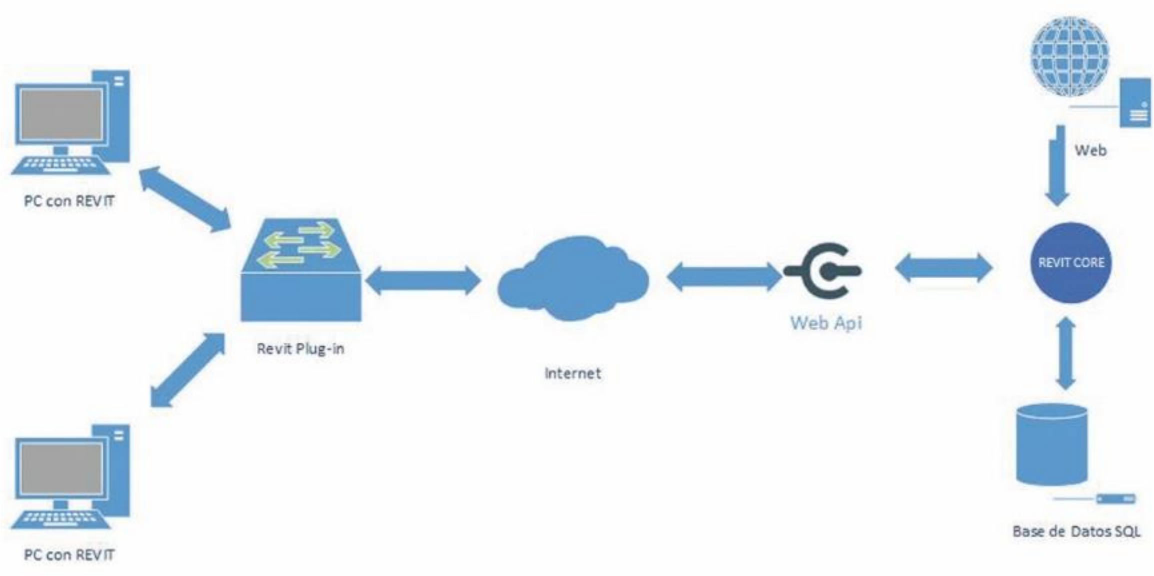


Figure 43. Computer architecture. HAR2013-41614-R, 2016.

Technical stakeholders work in 3D Revit models and the Revit parameters are mapped with the database fields of the documental web through a semantic recognition system. The plug-in filters BIMlegacy parameters from the rest of parameters of the Revit models and controls the possible changes made within these parameters. The non-technical stakeholders work on the website filling in the documentation fields, and adding photographs, drawings, and reports.

Synchronisation is the main characteristic of BIM. For that, the prior definition of a common completing space, a WAN (Wide Area Network) server, was required to share the data. A WAN server is automatically created when downloading the plug in from the website. This WAN server allows the hosting of central HBIM models where all the technical stakeholders can work together in real time. The automatic creation of a Wide Area Network (WAN) server when downloading the plug in was a requirement that the heritage team proposed to the IT team to improve the workflow.

4.2.3.2 BIMlegacy interface

The interviewees agreed that the platform should be user-friendly and simple to be useful. BIMlegacy was designed with a simple and intuitive interface to facilitate its use. The graphic design conveys heritage values with the technological BIM principles. It has eight screens with a lateral navigation bar with the following sections: management, general data, sectors, BIM, manuals/templates, images, graphic information, as seeing in Figure 44.

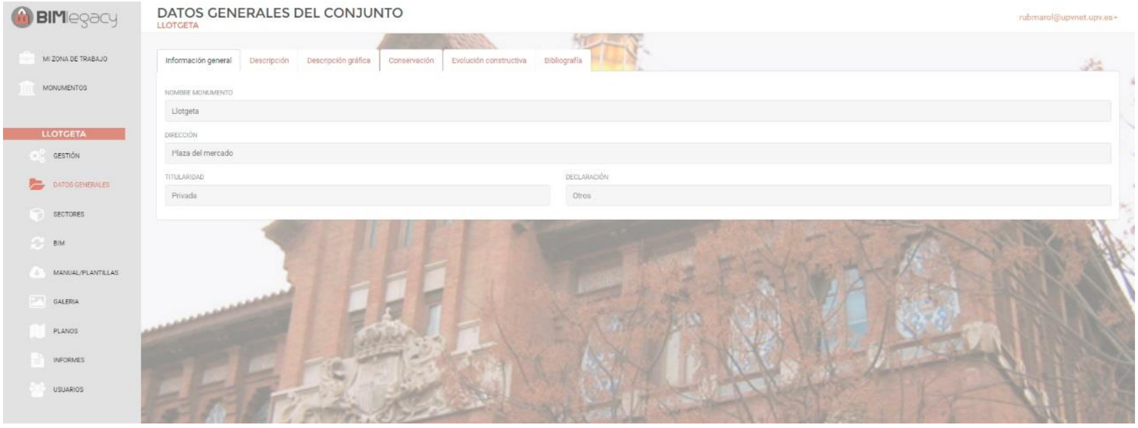


Figure 44. BIMlegacy worksite interface. HAR2013-41614-R, 2016.

- *Management* is a section where the monument manager can invite other participants, control the roles, and add the essential information.
- *General data* allows the addition of the monument information, fiscal data, written and graphical description, preservation condition, constructive evolution, and bibliography.
- *Sectors* section directs the stakeholders to the various parts of the monument. For example, if the monument is a church, one sector can be a chapel, another sector can be a vault.
- Complementary HBIM files are added In the *BIM* tab (a.e. BIM families, HBIM templates, and point clouds).
- *Gallery* contains pictures and drawings of the monument. For example, old pictures that need to be archived as cultural documentation.
- *Plans* has all the sections, facades, and plans of the current project or previous projects performed in the building.
- *Reports* is the section designed to upload any kind of reports of the building related to the current project or previous projects.
- *Users* is the section where users can be managed, and roles can be reassigned. This tab should be managed by the project manager.

4.2.3.3 BIMlegacy workflow

The goal is that users focus just in their own work and not in the website functioning. Basically, three group of people can use the platform: (1) technical stakeholders, who use the website as a secondary work space where they can download useful files (a.e. the plugin, the BIMlegacy template, and the HBIM families) and consult information; (2) non-technical stakeholders, who use BIMlegacy as HBIM main workspace to fill documentary fields and load reports; and (3) general public or visitors, who use it as consulting website to search historic-artistic information. Visitors do not need to be registered to benefit from the information archived in BIMlegacy. Nevertheless, not all the information in BIMlegacy is accessible for visitors, it is filtered to preserve the privacy of monuments.

4.2.3.4 Database fields of the platform

Three levels of documentation were created to order and divide and filter the information in the database, from general to specific: monument, sectors, and items. Those levels are directly related with these items in Revit: project file, families, and sub-families. Monument information is the generic data of all the monument (a.e. monument style, location). Families are constructive units (a.e. arc, volt) and their information fields are related with specific information of the constructive element (a.e. constructive system, material). Items are single elements that need to be registered and documented due to their singularity or values (a.e. a carved stone) and the information associated (a.e. author, technique). Items are sub families of Revit. Thus, the information of these three levels of the database can be synchronised with just one of the three types of Revit items previously named.

The platform searches for the ID of the HBIM elements to synchronise with the work website. Each family or item will belong to a BIM category (a.e. floor, celling, and column), Figure 45 represents the structure of the database, which was comprised of tables and their relationships. Each of the tables of Figure 45 is a property set and the primary keys of such tables of the database. The structure of the database was required to develop the database of the platform, without this structure is very difficult to develop such platform.

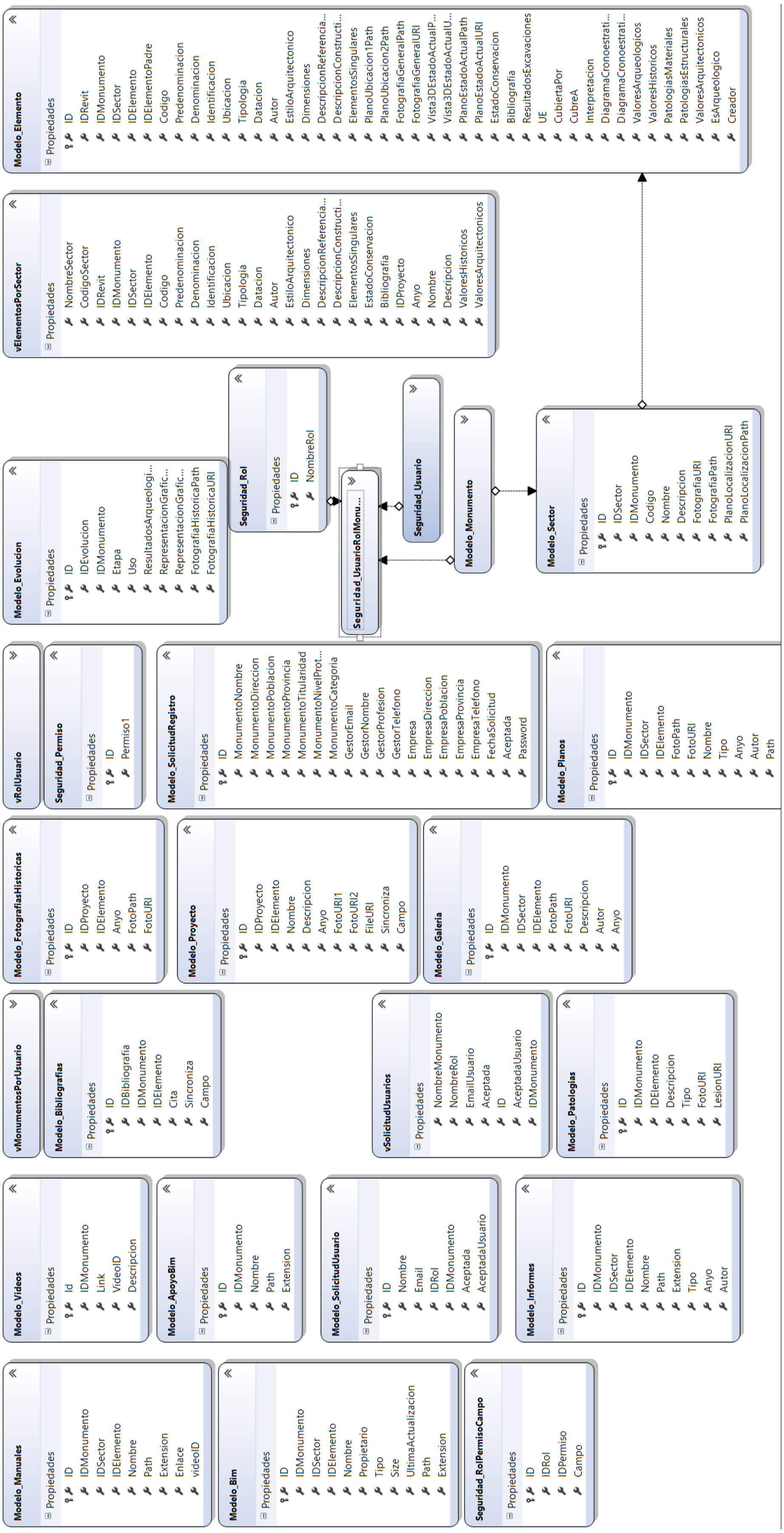


Figure 45. Computer architecture of BIMlegacy platform. HAR2013-41614-R, 2016.

The Revit project parameters are synchronised with the monument website fields. The Revit family parameters are synchronised with the sector website fields. Figure 46 represents the sub-families' parameters in Revit are synchronised with the singular elements fields. Each of the family of the model has not just geometrical information but information associated. As is showed in Figure 46 each family type has different parameters depending on its nature.

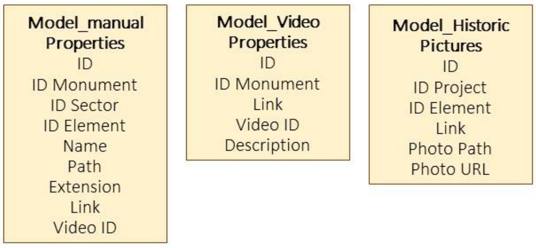


Figure 46. Properties of the families in the database, 2016.

These fields are assimilated as Revit parameters in the BIMlegacy Template, previously created in this research project. All the Revit parameters liable to be synchronised with the work website have the HBIM characters starting with the letters BIMle., see Figure 47.

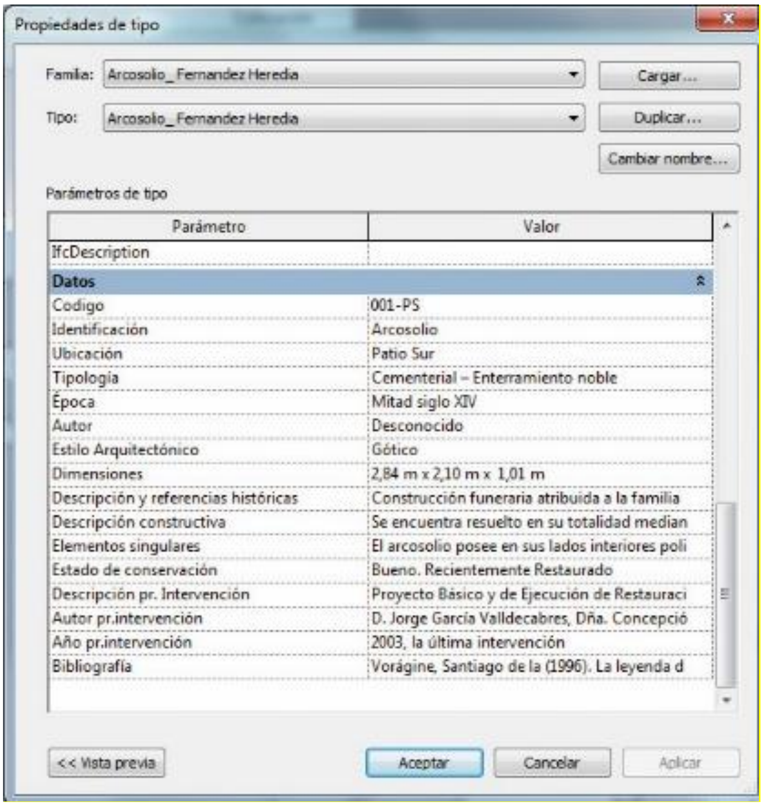


Figure 47. BIMlegacy parameters with the prefix BIMle. in Revit, 2016.

Regarding the permissions, fields have editing permissions depending on the professional profile. Each stakeholder can visualise all fields and edit exclusively those fields with edition permission. Each professional profile can fill just their discipline fields. Technical stakeholders, who are more liable to work with BIM, can insert, edit, and visualise the fields form the Revit software. Non-technical stakeholders, who do not work with BIM software, can insert, edit, and visualise different fields from the portal web.

4.2.3.5 BIMlegacy user tests

This platform prototype has been tested in twenty computers and devices from exacting standards HP tower computers with 32GB of RAM memory and Nvidia GTX 1080 Ti graphic card, to simple laptops with 8GB of RAM memory and basic graphics. All computers had windows operating systems and commercial antivirus software. Different issues emerged when doing the testing, but the most problematic points of its functioning were the automatic emailing, the permissions of the fields, and the correct installation of the plug in different operative systems. Those issues were solved within the next version of the platform explained in section 4.3.3 of this doctoral thesis.

4.2.3.6 Modelling files of BIMlegacy

BIMlegacy requires specific heritage HBIM files to support its use in real projects. The BIM Execution Plan (BEP) is the document that contains the tactic and methodological planning when using BIM. BIM Execution Plan is created for managing the delivery of the project. This in turn is split into a 'pre-contract' BEP, in response to the Employer's Information Requirements (in other words, comparable to 'contractor's proposals' in a Design and Build contract) and a 'post-contract' BEP which sets out the contracted delivery details. The heritage team designed a BIMlegacy HBEP template in order to provide it to future platform users since there were no templates available on the market. It was performed after a great analysis of the uses in HBIM and taking as reference important BEP templates (Dainty *et al.*, 2017).

Also, a heritage Revit template was required. Templates are empty files used to start the projects according to quality standards in response to the project organisation, the development planning, the optimisation of workflow, the nomenclature control, and the definition of appropriate views (a.e. international standards, such as ISO or DIN). In order to design the heritage template, the standardisation of the characteristic elements of the monuments were sought.

In conclusion, BIMlegacy is an online platform that allows data unification in real time and independently from the stakeholders' location. This platform performs as a database server, as well as a workspace for stakeholders who do not model in 3D (a.e. property, archivist, planning consultant, monument manager). All data should be held in the online server; nevertheless, access permissions could be applied to the different folders. This platform was used to perform San Juan case study.

4.2.4 CASE STUDY 2: SAN JUAN PROJECT

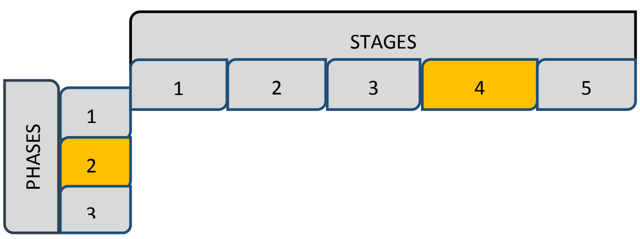


Figure 48. San Juan del Hospital of Valencia. Visitvalencia website, 2017.

4.2.4.1 Case study description

BIMlegacy protocol-2 (Figure 42) and BIMlegacy platform, previously created were applied to San Juan del Hospital's Historic-Artistic Grouping of Valencia that comprises the church, a convent, a cemetery, annexed buildings, and a courtyard, Figure 48. During the twentieth and twentieth first century the building has had various restorations, but further interventions are still needed as well as preservative maintenance. This is the reason because HBIM could be an interesting methodology to manage San Juan interventions and maintenance. San Juan stakeholders were about to start a new intervention and after explaining what BIMlegacy prototype was, they decided to get involved in the research.

San Juan del Hospital of Valencia was declared National Historic Artistic Monument by decree on 1943 (BOE 16.04.1943). This monument stands out by their preservation tradition, path of work, and its great master plan (García Valldecabres, 2010a).

The Church of St. John's Hospital in Valencia, Spain, is the oldest church after King James I's conquest of 1238. It has undergone a series of interventions in its past (Alonso Durá and Mas Millet, 1998). The constructive evolution of the building is now known due to the research carried out by analysing the documental sources and reading the walls (García Valldecabres and González López, 2014).

The priest, Mr Salvador Moret, first chancellor of the church after the reopening in 1967, was the main instigator of the rehabilitation, though it had many other supporters. Among these supporters, Rosa Rodríguez, Mr Elías Tormo's daughter-in-law and director of the Archive of the Kingdom of Valencia, stands out for her valuable contributions. She defined the basis of the documental register and the researching lines of the historic-artistic research.

Alejandro Ferrant's role was also indispensable. He was a monuments restoration architect since 1929, intervening in Oviedo's and Santiago de Compostela's cathedrals and in Santillana del Mar's and Toro's collegiate churches. He was also involved with the cathedrals of Palma, Lérida, Tarragona, and Valencia, as well as in the monuments of Ripoll, Santes Creus, and Poblet. As the restoration architect for the monuments in the fourth zone, he committed to the project, directed, and encouraged the intervention sets.

During the twentieth century it is possible to establish five outstanding events aimed at the restoration and preservation of the building of the hospital group:

(1) The historian Fernando Llorca's doctoral thesis, titled *San Juan del Hospital de Valencia. Fundación del siglo XIII,* presented and read in 1919 but published in 1930.

(2) April 5th, 1943, Declaration of Historic-Artistic Monument of National Nature. It was founded by Malta's Order based on their sensitivity and concern. The procedure started due to the Provincial Commission of Valencian Historic-Artistic Monuments unanimous agreement in the meeting held on November 21st, 1940. This meeting was requested by José Caruana, Reig de Lairean and Bauro, Baron of Saint Petrillo, the spokesperson for the History Academy and a distinguished member of Malta's Sovereign Order. In the meeting, there was the opportunity to declare the church, with its adjoined chapel, a historic-artistic monument. It is on December 14th, 1942, during the meeting held by the Academy after knowing Elías Tormo's considerations, that the church and the chapel are established as Historic-Artistic Monument of National Nature, which was published April 5th, 1943, in the BOE. A document that dates the construction of the church between 1238 and 1261 also specifies that this was the first Christian church of the just-conquered city by King James I, as well as it being the headquarters for Saint John's Order.

(3) In 1966, the Opus Dei Prelate took the responsibility of the pastoral care as well as to safeguard the preservation and recovery of the church.

(4) The agreement signed in 1993 between the church and the Culture, Education, and Science administration of the Valencian Government in order to cooperate and encourage *The Global Recovery of San Juan del Hospital of Valencia*. Ms Margarita Ordeig Corsini, director of San Juan Museum of Valencia, promoted the generation of San Juan Master Plan and the creation of San Juan Foundation ("Fundación de la Comunidad Valenciana Conjunto de san Juan del Hospital de Valencia") on October 22nd 1997.

(5) The composition of the main blueprint of the church, which was participated by the Universitat Politècnica de València.

Throughout these years, graphical documents were created in which it is possible to see missing buildings that show the historical importance and the singularity of the development. In the general blueprint of the Xerea's neighbourhood of the Historic Downtown there are drawings of the remains of a Roman Circus from the Imperial period, first century AD. Moreover, the Arabic wall itinerary of the city between the ninth and tenth centuries, the door named Xerea, and the remains of Islamic houses are depicted in a different blueprint.

Since the early twentieth century the Church of St. John's Hospital has been the focus of multiple projects and interventions to recover its value. Some of these projects have been accomplished while others have remained on paper only. The last registration- intervention project in San Juan called "Refundido del Proyecto Básico y de Ejecución de restauración y limpieza de fachadas del Patio Sur de la Iglesia de San Juan del Hospital" (hereinafter called "San Juan project") was performed using BIMlegacy protocol and platform to evaluate BIMlegacy efficiency in a real case study.

Different organisations and professionals were involved in this project such as La Fundación de San Juan del Hospital de Valencia, ERDI Integral S.L., and the research group integrated in the Instituto Universitario de Restauración del Patrimonio of the Universitat Politècnica de València (the IRP), a public Spanish institution dedicated to promoting heritage conservation research and practice. This research group have developed the San Juan project and the BIMlegacy Platform within the last four years, among other research projects with the coordination of the works by Ms Isabel Jordan Palomar, author of this thesis and the supervision of Prof. Jorge García Valldecabres. The specific contribution of this doctoral thesis within the designing BIMlegacy platform was as 3 years involved in the project as BIM manager is specified in section 3.3.2.

4.2.4.2 Case study justification

San Juan del Hospital of Valencia was chosen as case study since it gathers a set of characteristics and circumstances that make it ideal: it is a medieval historical building with complexity regarding constructive phases, and it has a wealth of information that provides the site's knowledge.

San Juan is a very interesting building regarding its typology and architectonic style, Mediterranean Gothic, which allows the standardisation of the constructive elements into Revit families. In the gothic architectonic style, the constructive and decorative paters are repetitive, a logical fact when considering that in the Middle Ages construction masters had a limited number of models and they did not search for individuality or originality. They used to repeat patters of close buildings and then adapt them to the location as Dr Felipe Soler Sanz explains (Sanz, 2014).

San Juan has the typical characteristics of historic buildings: various historical phases, re-use of structures and materials, pathologies and degradations. Thus, all the specific parts of BIMlegacy protocol can be applied in this asset. Its multiple historical phases will help to perform 4D BIM, which will provide factual data to continually improve the protocol. In addition, different heritage disciplines have been involved in San Juan (a.e. archaeology in extension, stratigraphic wall, metric, systems engineering).

Finally, San Juan was widely studied, and it is very accessible since two members of the research team are linked to la Fundación de San Juan del Hospital.

4.2.4.3 Case study objectives

This case study aims to improve BIMlegacy protocol and platform through its application in a real case study, San Juan project. The objectives were:

- To know the real requirements of the stakeholders in San Juan who are related with the interventions and conservation of the buildings.
- Apply BIMlegacy protocol-2 and use the platform in the San Juan project, this means register San Juan using HBIM technology and document it.
- Evaluate the case study results with semi-structured interviews with San Juan stakeholders.

4.2.4.4 Research process of San Juan case study

The case study method (Yin, 2009) was used. Qualitative research techniques have been used since it is an innovative-experimental research of social nature. The scientific techniques used have been documental analysis and semi-structured analysis.

Steps 1 and 2 of BIMlegacy protocol-2, see Figure 42, have been implemented in the registration of the San Juan project following these activities, Figure 49:

Implementation

- Documentary analysis
- 4D modelling
- Management of architectonic, archaeologic, and historic information.

Evaluation

- Semi-structured interviews with San Juan stakeholders
- Analysis of the interviews
- Conclusions of the evaluation

Figure 49. Main activities of the San Juan case study, 2017.

The implementation of the case study consists of the planning of the project strategy, the documental analysis of the monument, the laser scanning of the site, the 3D HBIM modelling and the management of the architectonic, historic, and archaeologic information.

BIMlegacy was then evaluated with San Juan agents through eight semi-structured interviews. In these interviews the protocol and the project results were analysed, and the stakeholders separately analysed the tasks they had been developing. The interviewed were: the director of San Juan, the computer graphics manager, the museum director, the tourist guide of San Juan, the heritage inspector, the urbanism architect, the maintenance technician, and the contractor.

These interviews have been transcribed and analysed with the scientific tool named NVivo, specifically designed for qualitative research. From this analysis some conclusions of the evaluation of BIMlegacy protocol-2 have been labelled.

4.2.4.5 San Juan findings

<u>San Juan Project</u>

A new intervention in San Juan historic was about to begin, named "Refundido del Proyecto Básico y de Ejecución de restauración y limpieza de fachadas del Patio Sur de la Iglesia de San Juan del Hospital", and after explaining what BIMlegacy prototype was and its benefits, the San Juan Foundation decided to do it using BIMlegacy protocol and platform.

The project lasted one year approximately one year, and ten people were involved in total:

- Heritage architect, manager of the project, 22 years of experience.
- Architect, experience as a historian, 15 years of experience
- BIM manager, 4 years of experience.
- BIM modeller, 2 years of experience.
- Systems engineer, 14 years of experience.
- Technical architect, construction manager, 12 years of experience.
- Archaeologist, 18 years of experience.
- The director of San Juan, monument manager, industrial engineer, doctor in theology, rector of the church, 3 years of experience.
- The computer graphics manager, cultural diffusion, Degree in Advertising and Public Relations, 3 years of experience in San Juan and more years in similar works.
- The director of the museum, archivist, artistic manager, Professor of Drawing, degree in Fine Arts, 25 years of experience.
- The contractor, technical architect, 20 years of experience.

Different stakeholders were more actively involved depending on the planning of the project. In the first stage, the archivist and the monument manager had higher workloads while in the last stages of modelling the architects, the BIM manager and BIM modeller had higher workloads. The results of the different steps are described below:

<u>Step 0 ASSET INTERVENTION STRATEGY WAS APPLIED</u>

<u>General exploration of the building</u>

A general exploration of the building was performed evaluating the structural condition, the materials degradation, and the systems antiquity; which was considered acceptable due to the preventive conservation performed in San Juan during the last years.

It was necessary to understand the client brief, in this case the client or owner has the Sacred Roman Catholic Church, specifically the Opus Dei Prelacy. It is directly managed by San Juan Foundation and the person in charge is Dean Priest Carlos Cremades Sanz-Pastor.

The contract to develop the project was performed through the pre-contractual BEP. They determined the contract, warranty, and conditions of the project. The monument manager documented the contract information within the BIMlegacy platform (interview with the heritage architect).

The architect documented in BIMlegacy the analysis and recognition of the constructive elements and materials. The information related to the building condition was archived in BIMlegacy focusing on the structural elements, the materials degradation, and the condition of mechanical and electrical fittings. The building condition was considered good due to the careful preservative maintenance performed on the monument during the last decades (interview with the director of San Juan museum).

Significance and value

It is of paramount importance to know the heritage asset before executing any kind of intervention, project or scientific research. The values and relevance of the heritage site were studied through the analysis and synthetisation of a large amount of historic, architectonic, artistic, and archaeological information found in San Juan museum, and in governmental and personal archives (interview with the systems engineer)

The UNESCO recognised San Juan of Cultural Interest due to the buildings multiple values and significance (Labadi, 2013) . It is the oldest Church of Valencia after the Cathedral; it was founded by the important military-religious order of the Hospitallers and the religious order still has a connection with the Church; and it has the characteristic and original Mediterranean Gothic style. The archivist and architects studied these values and the relevance of the historic asset after synthesising a great amount of documentation. The archivist then added this information in BIMlegacy work website.

Archival records

The historic department of San Juan has incredible documentation work during the last few decades, which would be impossible to capture completely in this doctoral thesis. Thus, the researchers refer for more historic, artistic, archaeological or architectonic information to the Plan Director de San Juan, the different actions developed in the Proyecto Raphael (1996), the doctoral thesis of Prof. Jorge García Valldecabres, other academic documents, specialised books, and rigorous reports (Salvador García, 2016; García Valldecabres, 2010b; Crespo Godino, 2006; Ordeig Corsini, 2000; Llorca, 1995). A vast number of volunteers, students, and workers of San Juan have collaborated during decades to generate the documentation that allowed us to have such high quality information to use and add to BIMlegacy (Ordeig, M. and Fernandez, M., 2007; Ordeig Corsini, 2000; Lassala Bau, V., et al., 2000).

The historian and art historian of San Juan performed the data recollection (Ordeig and Fernandez, 2007; Ordeig, 2000; Lassala Bau et al., 2000). It implied a search in archives, private collections, historic cartography of the city, and a special bibliography. Among these, San Juan museum, the Municipal Archive, the Kingdom Archive, and the Region Archive stand out because of the considerable number of sources obtained. The graphical documents founded can be divided into photographs, etchings, and blueprints. The latter belong mostly to the different architectonic surveying and projects that were used during the interventions in San Juan. San Juan is an expiatory temple, which means that the improvements or refurbishments in the buildings depend on the congregation donation. This fact resulted in many minor interventions over time.

The research group generated a synthesis of this massive amount of information, within the framework of different research projects, the main one being the previously coated project

El diseño de una base de datos, modelo para la gestión de la información y del conocimiento del Patrimonio Arquitectónico (García Valldecabres et al., 2016). Such synthesis was performed in accordance with BIM philosophy and BIMlegacy protocol. These tasks were developed by Ms Concepción López García, heritage architect, Ms Elena Salvador García and Ms Remedios Zornoza, and were guided and led by Ms Margarita Ordeig Corsini, art historian and manager of San Juan museum.

The archivist and the art historian entered each piece of information in its specific field of the BIMlegacy work website. The website synchronises this information automatically with the HBIM model database, so that the technical stakeholders could see all the information that non-stakeholders were adding in real time. The fields are modifiable and visible depending on the assigned role.

Valuing property

The evaluation of the economic and social opportunities is one of the steps of the protocol in step *0. Asset intervention strategy* was already stabilised in The Master Plan of San Juan. The San Juan Foundation is in charge of evaluating the economic and social opportunities, such as, searching for pubic economic foundations, integrating the monument within city tours and providing a social layer in the heritage activities of the asset (interview with the director of San Juan).

The monument manager and the cultural broadcaster (cultural diffusion manager) recorded these activities in BIMlegacy to document all the layers, and not just the architectonic one. The idea was that the local community and the tourists could check the sections that are available to the general public of BIMlegacy platform to disseminate cultural heritage within the society.

Master Plan

San Juan has a Master Plan that was published eighteen years ago, the Plan Director (Lassala Bau, V., et al., 2000). This document is remarkable because it is the first monument master plan generated in Valencia City. Mr Fernando Romero Saura recommended in Mr. Sergio Segura's master thesis to update the stipulations described in San Juan master plan and promote the future lines of it, such as the redaction of a maintenance and security plan. The monument manager was updated in BIMlegacy about the general criteria of this Master Plan, in the section of general information of the monument.

The architect in chief of San Juan, Prof. Jorge García-Valldecabres managed the property rights and the heritage site in the land register. He then updated the property report in BIMlegacy the property report and the relevant information regarding the land rights (interview with the architect in chief of San Juan).

Definition of the BIM Execution Plan (BEP)

The HBEP was designed following the precepts of BIMlegacy protocol. BEP is defined in the PAS 1192-2:2013 as a "plan prepared by the suppliers to explain how the information modelling aspects of a project will be carried out". This task was carried out by Mr Gustavo

Heredia Ortega, BIM modeller collaborator, with the supervision of the author of this doctoral thesis and Prof. Jorge García Valldecabres.

A generic BEP for heritage projects was designed, that was then added as a complementary guide of layer C of the protocol. Then, the specific HBEP for San Juan was developed by filling the HBEP with the specific casuistic of San Juan project. The HBIM BEP of San Juan project was updated in BIMlegacy, so that all stakeholders could consult its last version.

STEP 1. BUILDING REGISTRATION

San Juan project was performed following step 1. Building registration of the BIMlegacy protocol entailed: (1) definition of the historical evolution of the building; (2) the laser scanner data collection; (3) modelling the materials of the building; (4) modelling HBIM structural and MandE; and (5) the historic, artistic, architectonic, and archaeological documentation in HBIM.

The process started with the registration of the monument in BIMlegacy and the invitation of the involved stakeholders to the project, each one with their own role. San Juan stakeholders were in different geographical locations; this was ideal to prove the effectivity of BIMlegacy, to facilitate work online. The project manager performed the tasks distribution among the other stakeholders through BIMlegacy (a.e. the general exploration of the building, the definition of the strategy of the intervention project).

Definition of the historic evolution

Before modelling it is crucial to understand the building and its evolution. The academic master theses developed by Mr Daniel Crespo Godino and Ms Remedios Zornoza explained the historical and constructive evolution of San Juan. The doctoral thesis of Prof. Jorge García-Valldecabres helped to comprehend the metric pattern of the building due to the meticulous work of metric and mapping developed within it. The technical architect analysed these reports to have a clear understanding of the building evolution and to stabilise which historical phases that were more relevant and needed to be modelled in the HBIM Revit file.

Selection of equipment

HBIM modelling requires very powerful hardware devices as explained in BIMlegacy protocol. The BIM manager and BIM modeller performed a study of the possible hardware and software to use in this case study considering the required tools. The number of people modelling, the kind of internet connection, and the weight of the future BIM files were the criteria considered when selecting the equipment. The San Juan project had a capable IT team to solve the issues during the modelling and point cloud labours. Any BIM activity requires IT support to develop such a technological activity. In terms of hardware alternatives, the devices needed to be very powerful to move point clouds and manage heavy HBIM models. The chosen computers were HP Z420 of 6GB of RAM memory. The processor was an Intel Xeon CPU E5-1620 of 3.60 GHz and the system was of 64 bits processor.

In terms of modelling software different alternatives were studied:

- Archicad from Graphisoft was the software that initiated the BIM revolution and is still leading the market. It belongs to the multinational Nemestchek Group, since their acquisition in 2007. Archicad had the first BIM server and the Eco Designer app to perform energetic modelling. Its remarkable characteristics are: own online server, IT solutions that are updated each year, rendering engine of Cinema 4D (from Maxon company) and so high-quality rendering, and version checking totally integrated in a PDF optimised file, which helps the interoperability.
- Allplan is an intelligent and traditional software with 2D and 3D modelling. It is the BIM software where the second dimension is more widely used, which could seem easier for stakeholders who are not familiar with BIM. It has integral and surface evaluation, flexible floor structures, a large library of structural systems, a library of wood elements, limited interoperability, and good connection with measurements and cost software.
- Revit from Autodesk includes architectonic, constructive, engineering MEP, and structural modelling. Autodesk is one of the largest companies in the market having a great broadcasting and user feedback system. Its characteristics are: parametric elements to improve accuracy, bidirectional associativity (each change is automatically reflected in the entire model), construction modelling, good interoperability with point cloud, and an acceptable interoperability with IFC files.

Revit was the chosen software because it is the one that has more widespread consumer use, more users, better interoperability, a user-friendly interface, and acceptable tools to manage point clouds. In addition, it is the most powerful software in terms of an intrinsic database, and the one that has the most parametrisation options.

A plug-in to import point clouds in the Revit family files was needed. After studding the diverse alternatives in the market, PTS import from Autodesk was chosen because it was considered the most effective to import point clouds into Revit family files.

Creation of the server

BIM require a common space where the files could be synchronised, and the information can be shared. The WAN server was automatically created when downloading the plugin from the BIMlegacy website. This supposes a major advancement because it facilitates a CDE for all the technical stakeholders. The devices and computers directly related with the modelling could access the server using their own credentials. As is represented in Figure 50, the two BIM modellers and the two architects worked on this server. The information of this server was connected with the BIMlegacy website, so all stakeholders worked simultaneously visualising the changes that other team members were making.

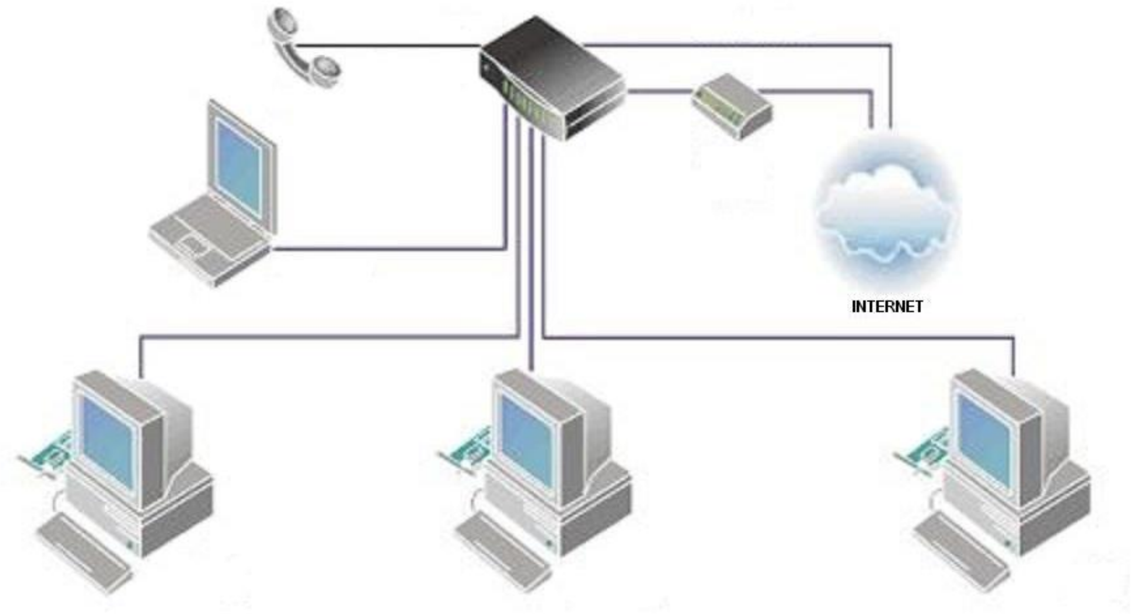


Figure 50. Network organisation to perform San Juan case study, 2017.

The server was articulated in different folders where the information was classified. The folders in the server were ordered by construction phases and then by disciplines. For example, inside the 03, execution project folder, there were the 03.01, architecture or 03.02, archaeology folder.

The BIM manager defined the nomenclature using the criteria defined in BIMlegacy protocol. The nomenclature of the cataloguing sheets of San Juan elements was taken as reference when naming the elements in Revit, and therefore the elements have the same name in Revit and on the work website.

Data collection with laser scanner

A scanner laser was chosen to do the data collection because it has proven to be a better system to document historic buildings condition with accurate measurements (Afsari *et al.*, 2016). Roca (2006) affirms that the terrestrial scanner defines a coordinates system X,Y,Z, which coordinates origin in the scanner machine and each point is associated with a coordinate and a distance. These coordinates define the three-dimensional location and position generating a relative system of coordinates related with the scanner machine.

After the scientific literature study, it was understood that a high accuracy data collection system was required to perform the architectonic survey. Therefore, the data collection process to perform the architectonic survey started with the laser data collection.

There has been an extended documentation and architectonic drawings of San Juan generated surveying caned out during the last decades. The architect in chief and the heritage architect, Prof. Jorge García-Valldecabres and Prof. Concepción López González, performed the last architectonic survey of San Juan with traditional methods including a chronology or time-line of drawings and surveys. Previous traditional data collections included blueprints, drawings, photography, and architectonic surveys from different époques. Even though there were such an extended architectonic information, San Juan project members decided to perform a laser scanner of the building to have the most accurate data collection.

Before starting the scanning, it was necessary to generate a **scanning plan** that is a scheme of where the scan is going to be located and where the spheres or artificial references are going to be placed. Without a good scanning plan, it is possible that certain areas of the building will not be scanned or will not be scanned correctly.

Technicians from Leica Scanner Company taught to some of the research team members, Mr. Rubén March Oliver, Ms. Remedios Zornoza Zornoza, and Ms. Elena Salvador Garcia, in a specific course the basis of scanning work field: the scanning process, the difference between natural and artificial references, the placement of the artificial references (a.e. sphere, target), how to name spheres, the different speeds of the scanner, and the different quality of digitalisation.

With this training the architects, technical architect, and BIM manager, performed different scanning in the building following the continuous linking sequence. Multiple scanner stations were required to cover the full asset of San Juan complex, fifty-seven scan locations were needed to cover the dimensions of the asset and corners to obtain the maximum extended laser scanning. Two scans were needed, the first one at the beginning of the project and the second one around one year after.

In the first one, the laser scanner covered the Church, the north and south courtyards, and even the asset roofs, and with a Leica Scan Station C5 with a complete visual field of 360º x 270º very high resolution with a range of 35m and scanning speed of 25000 points per second. Targets were used as artificial references to combine different scanner positions. A second scanning was performed using Faro Focus 3D to register specific pathologies that were not recorded the first time. The second time, spheres were used as artificial references, and a total of 15 scans were carried out in 15 different positions.

The **point clouds joining** process took place in the office using a powerful computer with 16GB of RAM memory. Each scanning positioning creates their own point cloud, and all these point clouds were united using Cyclone software the first time and Scene software the second time to create a three-dimensional point cloud with all clouds unified. The union process consisted of the pre-processing of the point clouds, when the software recognised the point cloud information (a.e. artificial references, natural references), the positioning, when the software emplaces and combine the different scans, the union of the different scanning, and the exportation of the united point cloud.

Once there was a unique point cloud, it was **cleaned** by eliminating all the irrelevant information that was captured what is technically named noise (a.e. people walking, cars, trees). The noise was cleaned by selecting those points that were not interesting and eliminating them. This process was quite manual since there is not an algorithm in the market that automatically selects those points that represent irrelevant information. During the second scanning, the irrelevant objects were moved away from the scanning scenario before starting and people and cars were warned to not enter in the monument since technical work was being carried out. This allowed the reduction of work in the office.

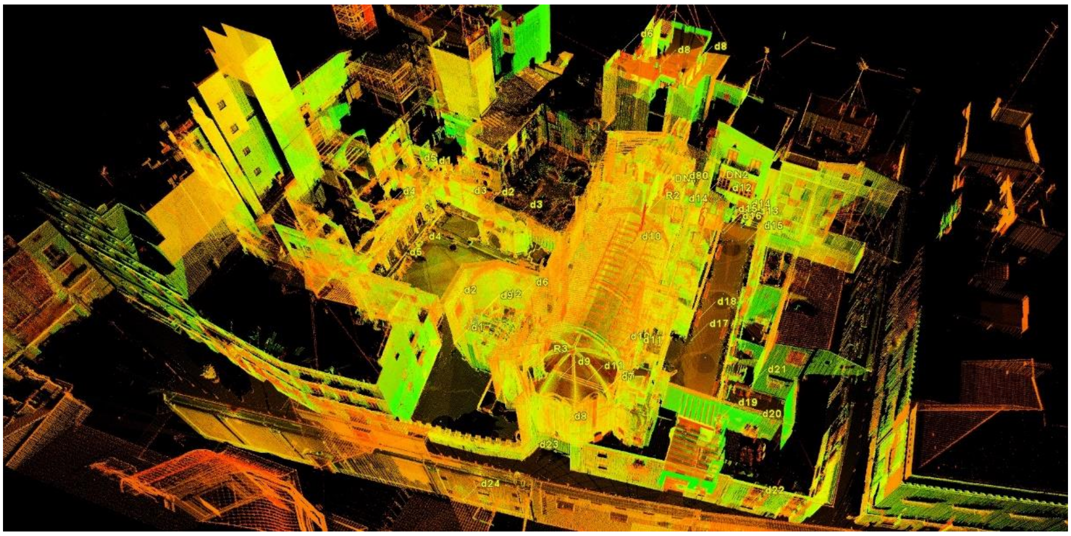


Figure 51. Data collection with the laser scanner in San Juan. Office work performed by Mr. Rubén March Oliver and Ms. Isabel Jordán Palomar, 2017.

The point cloud of all asset supposes accurate and exhaustive data of the current condition of San Juan, so it was used to model the existing state of the asset, Figure 51.

Heritage Template

There was not a specific heritage template to start a new Revit project. Nowadays, Autodesk only provides certain construction, architecture, structure, and systems templates. Templates are empty files that contain all the families, standards, view templates, and view organisers. The heritage template was designed within the BIMlegacy protocol-2 and platform and it was used to start San Juan project.

A new project was open using BIMlegacy historical architecture template, previously designed; then the users' profiles were generated in the BIMlegacy web to give access to the central model -that is the master file where all the changes done by other users can be seen-. San Juan was modelled taking the point cloud as framework.

General modelling

The general modelling supposed the most important workload in this case study. The HBIM modelling was performed with the software Revit form Autodesk version 2016. The general modelling achieved a Level of Development (LOD) of a 400 in the modelling of the existing phase of the building and lower LOD for historical hypothesis. San Juan model was created to use it during the whole life cycle of the asset.

The parts of the general modelling consisted of: importation of the point cloud, definition of the historical phases, modelling of the general geometry using levels and grids, and parametrisation and restrictions of the model, see Figure 52.

Methodology designed to perform general modelling with BIMLegacy

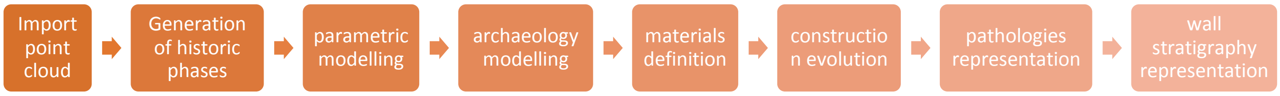


Figure 52. Steps to the general modelling in HBIM, 2017.

A new project was open using the previously created BIMlegacy template of Revit. The different subprojects and users of the central models were then created. A central model, hosted on the online platform, was created to allow the collaborative work between the stakeholders. The HBIM model included five sub-projects separated by disciplines: urbanism, architecture, archaeology, structure, and MandE.

The point cloud was then inserted in the Revit project in a .e57 format, the most standardised format and the one that provides more interoperability. The point cloud was fully inserted in one piece after considering splitting it in three different sections, but this idea was dismissed due to the possible coordination issues.

The workflow of collaboration was the cloud work-sharing. This is a method of work-sharing in which the central model is stored on the cloud. Team members use BIMlegacy to author changes in the model concurrently. In San Juan project six users were created, but just the BIM manager had full permission over the model. Each person opened the central model each day from his/her computer and performed the modelling. There was an automatic synchronisation each 15 minutes. The involved stakeholders were:

- BIM manager, 4 years of experience.
- BIM modeller, 2 years of experience.
- Heritage architect, manager of the project, 22 years of experience.
- Technical architect, construction manager, 12 years of experience.
- Archaeologist, 18 years of experience.
- The contractor, technical architect, 20 years of experience.

As Parenti (1995) said, the criteria to model is to start with a general approximation generating a panoramic vision, and then in a later phase, the model should be detailed and made more specific (Parenti, 1995). Thus, the criterion was modelling from the general to the specific in an inductive manner. The elements that were used were mainly the ones that were predefined in the BIMlegacy template (a.e. vaults, adobe wall, masonry pillars).

The modelling of the general geometry was done with Scan to BIM methodology, the emerging technology to transform point clouds in geometrical items, which was explained in the state-of-the-art section. The conversion of the point cloud into a geometrical 3D model was done with Cyclone plug-in for Revit and manually modelling over the point cloud, since the plug in only recognised flat surfaces. Thus, the scan to BIM process was semi-automatic, Figure 53.

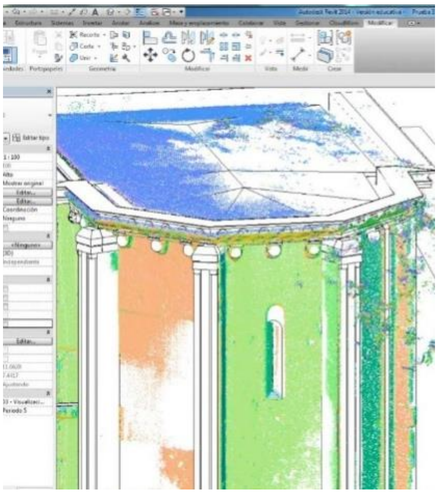


Figure 53. Modelling process based on the point cloud overlapped. Example of the Funerary Chapel of San Juan, performed by Mr. Rubén March Oliver and edited by Mr. Isabel Jordán Palomar. 2017.

A **general modelling** was performed building the general shapes of the building and the general locations of the site. The general LOD of the model was 400 considering geometrical modelling and quantity of information, Figure 54. The modelling of the existing phase was performed over the point cloud. Revit was detecting points and the geometrical shapes were built over the point cloud.

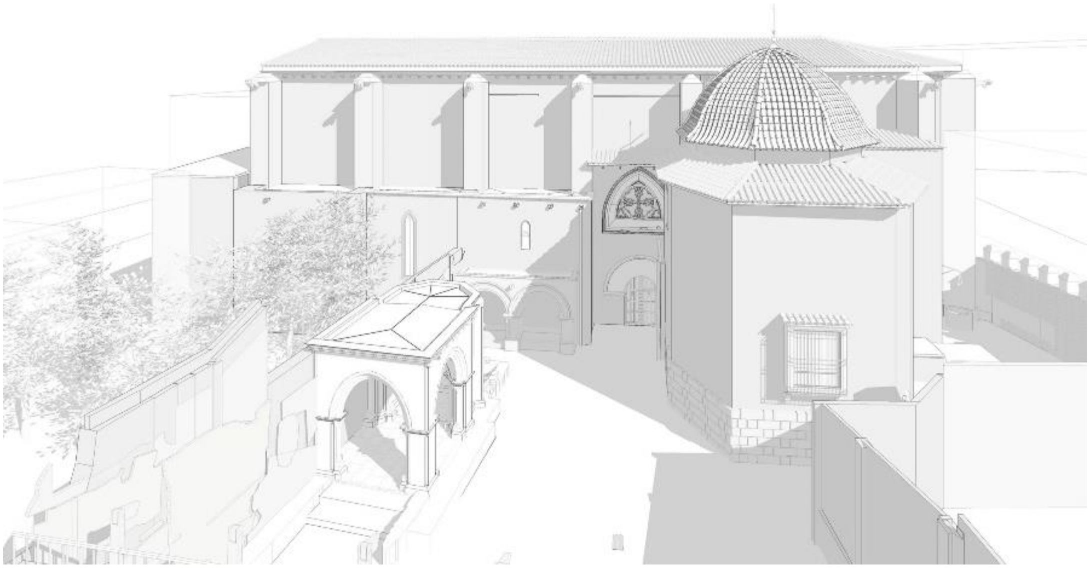


Figure 54. Modelling process based on the point cloud previously created, 2017.

This general modelling was parametrised as much as possible. A parameter is a numerical or other measurable factor forming one of a set that defines a system or sets the conditions of its operation. BIM modelling is called parametrised because restrictions, levels, and relationships programmed the model. For example, when a wall was built, this wall was programmed to be linked to the roof, so that if the roof moves, the wall will move after it automatically.

Specific modelling

The **specific modelling** was carried out detailing the virtual model through free shape elements; that are of high importance in heritage projects considering that it is necessary to represent pathologies, crashes, masonry bonding, and deterioration level. The alterations due to the passage of time, such as flaws and material imperfections, cracks, etc. were also represented as they were documented within BIMlegacy website.

As it is recommended in BIMlegacy protocol, items were initially modelled as they were designed in its origin, thus the elements created can serve to other users, and the work is more systematic and standardised. If the deformations and pathologies that were currently observed were drawn from the beginning, it would not be possible to apply historical phases.

Both external and internal libraries and Revit **families** were created. *Families* are files with sets of two-dimensional or three-dimensional elements already designed can be used in the projects and provide detail to the model. There are not many historic families on the market; hence, the design of our own families of heritage elements was posed. The repetitive elements, such as the characteristic gothic arc, were standardised in external parametrised families based on geometrical parameters. Mr. Rubén March Oliver, member of the research group and construction engineer, was the families' modeller and co-designer of these families. As a result, standardized BIM families with the most characteristic elements of the medieval architecture were modelled: Gothic arch, semi-circular arch, rose window, pilaster, round-arch flared window, pointed window, wall anchors, arcosolia, funerary steles, gargoyles, ribbed vault, and barrel vault.

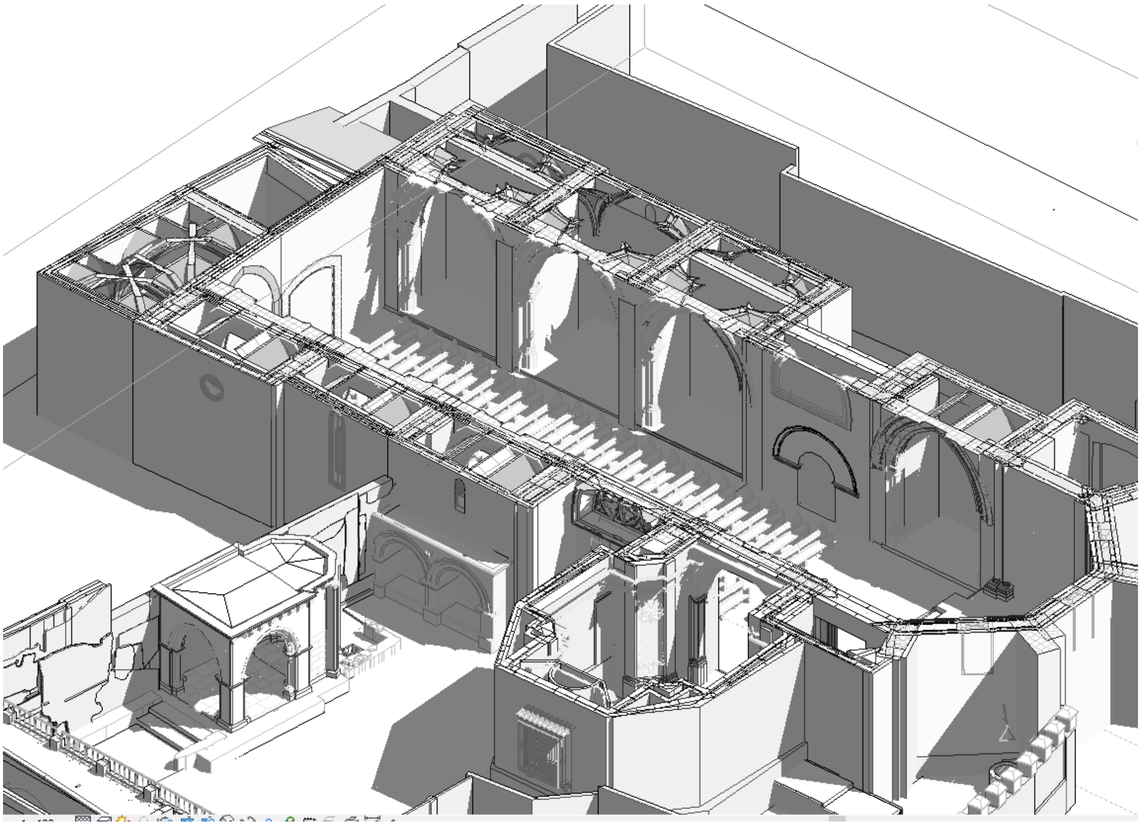


Figure 55. Process of performing the specific modelling including external and internal families. 2017.

To solve the rigidity of the BIM modelling, which was announced in the state of the art as a possible HBIM issue, many in site elements were modelled. In site elements are more flexible and can be adapted to complex geometries, as the heritage assets have. It means, instead of using the by default wall tool of Revit that is an orthogonal rectangle, in site wall was used to adapt to complex heritage shapes. This was useful to build twits, spins, partly demolished structures, broken elements, and chromatic alterations. All these shapes could represent the logic deterioration of heritage structures.

The capability of BIM software to model complex structures is an important concern among heritage community. In San Juan project it was demonstrated that it is possible to achieve a lot of detail and good quality architectonic survey using HBIM. However, it is relevant to admit that a high modelling ability is required to achieve such results.

The extremely complex elements, such as sculptures, were created with 3D nets and imported into Revit as is explained in BIMlegacy protocol, layer C, section 4.3.2.3. Specifically, the sculpture of the Virgin Maria that is placed inside the Funerary Chapel was modelled with this system by the historian restorer Mr. José Charco, collaborator of the project, and the works and BIM methodology was supervised by the architect, BIM manager, and monument manager.

The constructive definition of the model was performed within this step of BIMlegacy protocol. The constructive definition is intrinsically linked to the historical construction techniques, as is showed in Figure 56. Thus, important researching work was done to understand certain construction techniques as for example the adobe wall.

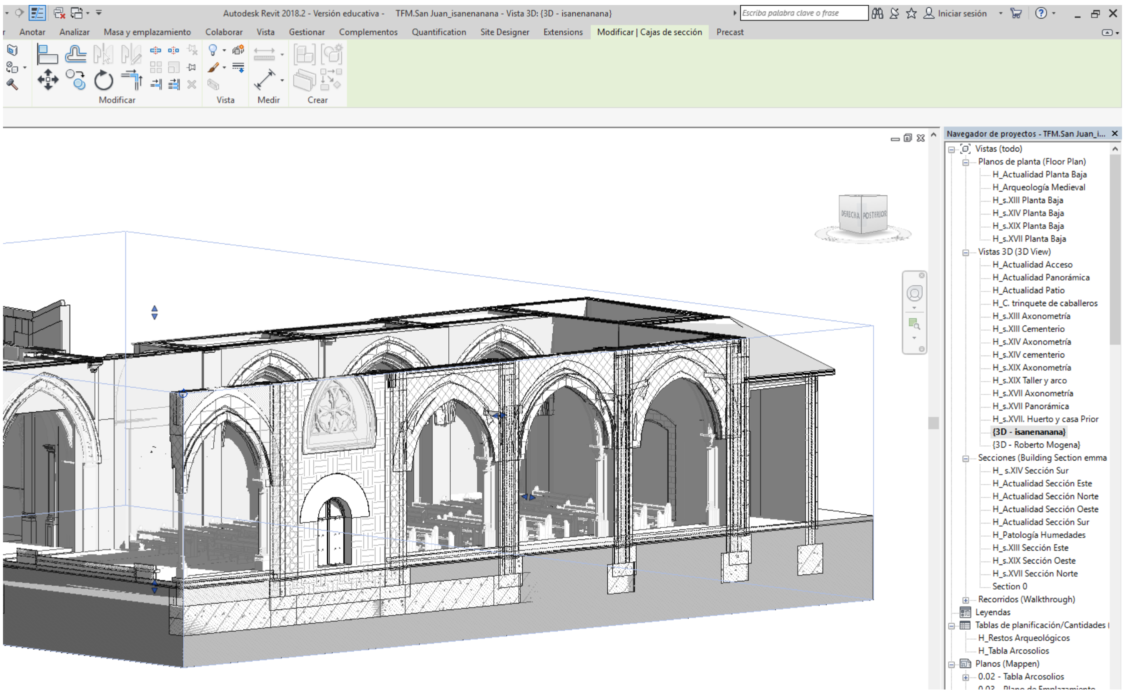


Figure 56. Constructive definition of San Juan. 2017.

The important constructive details were modelled in 3D as separate projects linked to the central model. Then they could be deactivated on the central model when it was necessary, and the model could be lighter. The modelling process has resulted in the creation of typical heritage constructive elements existing in San Juan. These are the double-wall stonework with interior stuffing, the connection between an arc and the masonry stuffing, and the ribbed vault linked with a gothic arc.

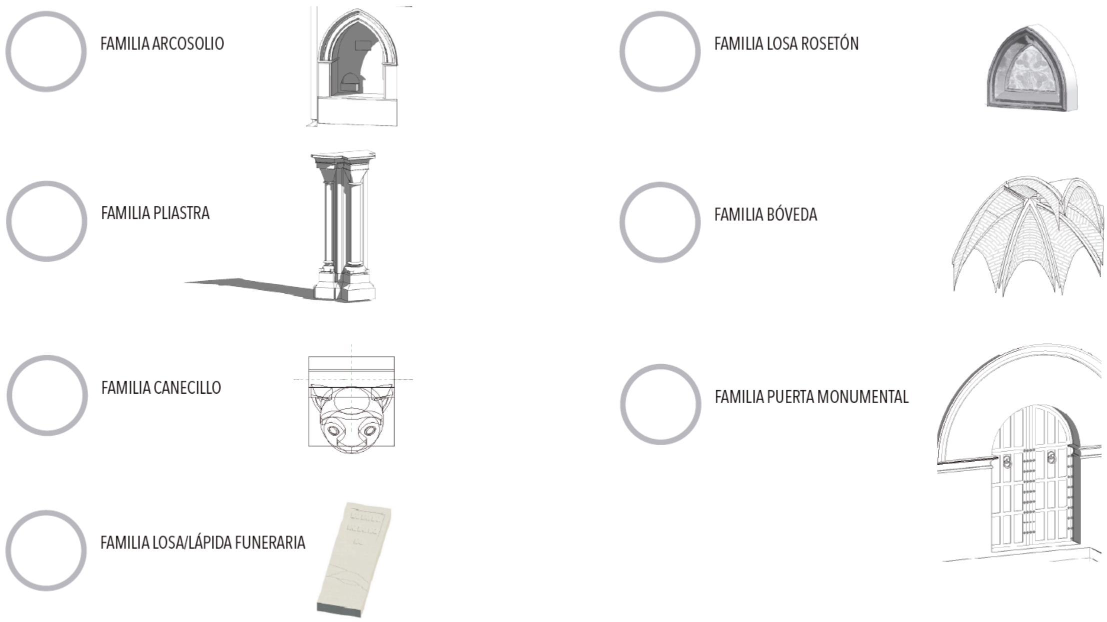


Figure 57. HBIM Revit families created in San Juan project. Mr. Rubén March Oliver and Ms. Isabel Jordán. 2015-2018.

Wall stratigraphy

Stratigraphy is a key concept to modern archaeological theory and practice. Modern excavation techniques are based on stratigraphic principles. The wall stratigraphy is the adaptation of this concept to architectonic walls in order to determine their dating and find out more about their historical evolution. As Camila Mileto stands:

“La estratigrafía muraria constituye una metodología que posibilita la identificación y documentación de los datos materiales legibles sobre la fábrica, tanto en el caso de un yacimiento arqueológico como en el de un edificio.” (Mileto, 1999: 80-93)

“Wall stratigraphy is a methodology that allows the identification and documentation of material data that are legible in the fabrics, both in archaeological sites and in architectonic buildings (Mileto and Vegas, 2003): 80-93)”.

Wall stratigraphy is a method that has different phases and implies a cognitive process to understand the constructive and historic evolution. Thus, in San Juan model the different stratums were represented in different historical phases with the constructive phases of Revit, creating a logic wall evolution.

Since San Juan model achieved a great level of detail after modelling over the point cloud, each stratigraphic unity was represented in a different phase according to the architectonic reports developed by Crespo (2006). It supposed the use of stratigraphy discipline within an HBIM model that is indeed a novelty concept in HBIM practice.

Modelling the material records

After analysing the previous information regarding materials and San Juan data, a library of materials of San Juan was created to provide materiality to the virtual model of the case study.

Together with the materials, the techniques used in the past to create such materials were also studied. The materials created were: Valencia earth wall, stonework, stone masonry, hard-packed earth, Arabic tiles, lime plaster and solid brick masonry, rough limestone, natural drying solid brick wall, and rowlock brick. This library could be reused for future projects.

Each material was listed in Revit schedules to provide a list of materials and the techniques associated with each material. Then each material was assigned to the geometrical shape of the virtual model using the property tool.

Modelling the degradation/condition details

The **alterations** that occurred due to the passage of time (a.e. flaws and material imperfections, crashes or seats, cracks) were represented. After different trials, the BIM manager stated that it was better to initially model items as they were designed in its origin, thus the elements created can be archived in BIMlegacy, and the work is more systematic and standardised. If the current deformations and pathologies are drawn from the beginning, it would not be possible to apply historical periods, Figure 58.

Figure 58.Conservation condition of San Juan, 2017.

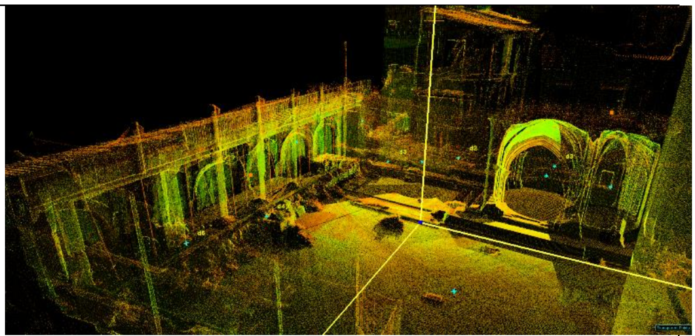


Figure 59. Point cloud to document the conservation condition of the construction, 2017.

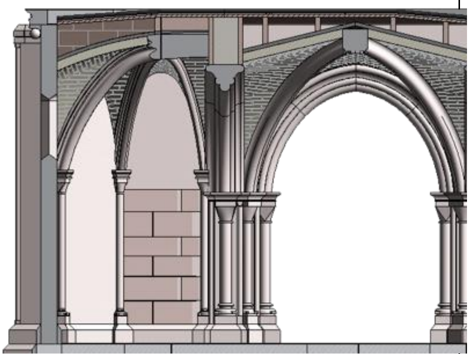


Figure 60. The modelling results of the application of BIMlegacy-2 to San Juan. Mr. Rubén March Oliver, 2017.

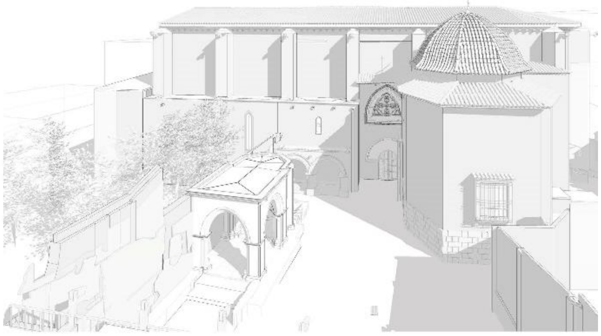


Figure 61. The modelling results of the application of BIMlegacy-2 to San Juan, 2017.

Archaeology modelling

Archaeology is fundamental to understand and situate the historic-constructive hypothesis as well as to document the monument, Figure 62. The information to situate the archaeological remains comes from archaeological reports generated in previous archaeological campaigns (Crespo Godino, 2006). After the documentation in BIMlegacy, the archaeological remains were modelled in a separated HBIM subproject and in three archaeological levels were created to order the archaeological remains according to historical periods: Roman, Arab, and Medieval.

Each archaeology remain was built in different archaeological packets to have an ordered model. These archaeology units had the information of the archaeological reports.

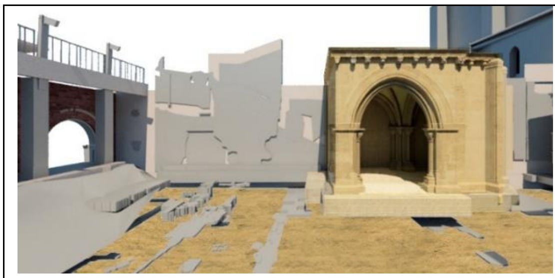


Figure 62. Archaeologic remains modelled in San Juan's HBIM model, 2017.

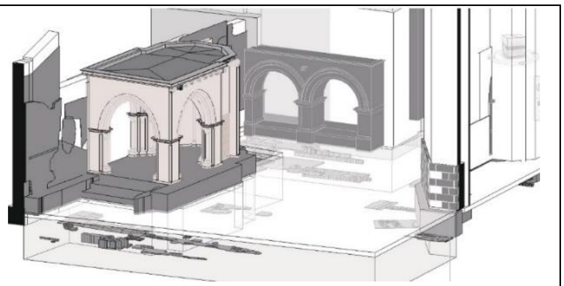


Figure 63. View of archaeologic remains modelled in San Juan's HBIM model, 2017.

The archaeology modelling allowed to reunite a high quantity of archaeological information with the architectonic information, which resulted very useful to understand and resolve certain historical hypothesis, Figure 62 and Figure 63.

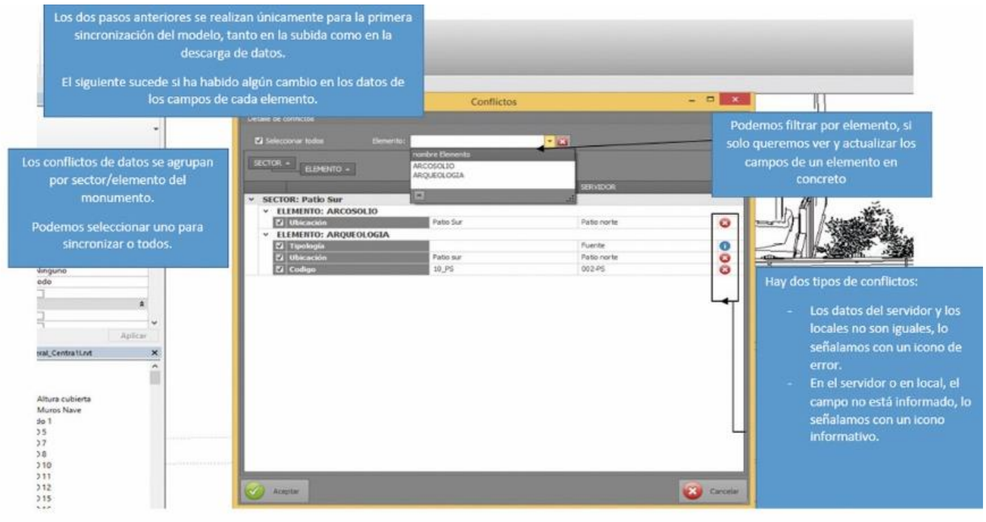
<u>Historical phases modelling</u>

The Revit tool constructive phases were used as historical phases, as is recommended in BIMlegacy protocol. Historic buildings accumulate several shape and structural changes during their long-life cycle. The constructive evolution of the building was known due to the documentation in BIMlegacy workspace. Five previous historical phases were modelled but with lower LOD since there was not enough detailed information to recreate how the building was in ancient times very detailed. Those historical phases must be documented within the HBIM model but with less LOD since there was not enough information in the past about how the asset was. The definition of the historic-constructive evolution in San Juan was done using BIMlegacy information, previously added by the archivist. The most relevant historical phases were represented in the HBIM model and documented in BIMlegacy. Those were: XIII c., XIV c., XVII c., and XIX c.

Figure 64 represents the plug-in that synchronised the Revit files with the documental database, which was fully developed in Spanish language. The dark blue boxes are the messages that appear when using the plug in in Spanish, which have been translated into English in the light blue boxes.

The first synchronisation entails the updating of the model. If there is any change in the model or in the database a new synchronisation will be required.

It is possible to filter just one element in case it was just wanted to update the information of a specific element.



The conflicts are grouped by sector/element of the monument.
It is possible to synchronise just one conflict or all at once.

There are two types of conflicts:

- The information of the historic database and the information of the model are not the same, it is represented with an error icon.
- In the historic database or in the model, the field is not fulfil, it is represented with an informative icon.

Figure 64.Plug-in that synchronises the Revit files with the documental database. HAR2013-41614-R project (developed in Spanish). 2017.

The existing phase is the one that was modelled in first place since the point cloud provides a complete information of this phase. The oldest phase was modelled following the logic order of history, the XIII c. phase, and then the other phases in chronological order. Each element has their own creation phase and demolition phase (Alba-Rodríguez *et al.*, 2017). When applying the phase filters, the virtual construction of the asset appeared automatically.

One of the issues of using constructive phases as historical hypothesis was that the point cloud could not be added exclusively to the existing phase, instead it appears in all phases. This problem was solved by hiding the point cloud in the historical hypothesis phases.

Modelling historical hypothesis is extremely important since heritage buildings have an evolution that need to be represented. The use of this tool represents a notable contribution for HBIM methodology.

<u>MandE modelling</u>

San Juan is an architectonic complex, mainly exterior, with not many systems, only electricity, plumbing, and a drainage system. It has not heating, air condition, or telecommunication system. As most of the systems are outdoors, they have even less systems complexity. This work was done by the BIM modellers and the BIM manager.

<u>HBIM documentation</u>

It is necessary to know the system to synchronise the information to rightly document the model to preserve and restore the built heritage. Thus, the first tasks were inventorying its parts; cataloguing it through BIMlegacy; registering the technical data; documenting the important people that habited the building; and documenting the designers of the building, the values in terms of local, national and international.

The synchronisation of the historic and documental information with the HBIM model was constantly performed with BIMlegacy, Figure 65. In this research participated Mr. Rubén March Oliver, Ms. Elena Salvador Garcia, and Ms. Isabel Jordán Palomar. The historic and archaeological information was introduced through the Revit plug-in that allowing the synchronisation of historians and archaeologists. Technical stakeholders and non-technical stakeholders were in different geographic locations, different offices, so this plug in was fundamental.

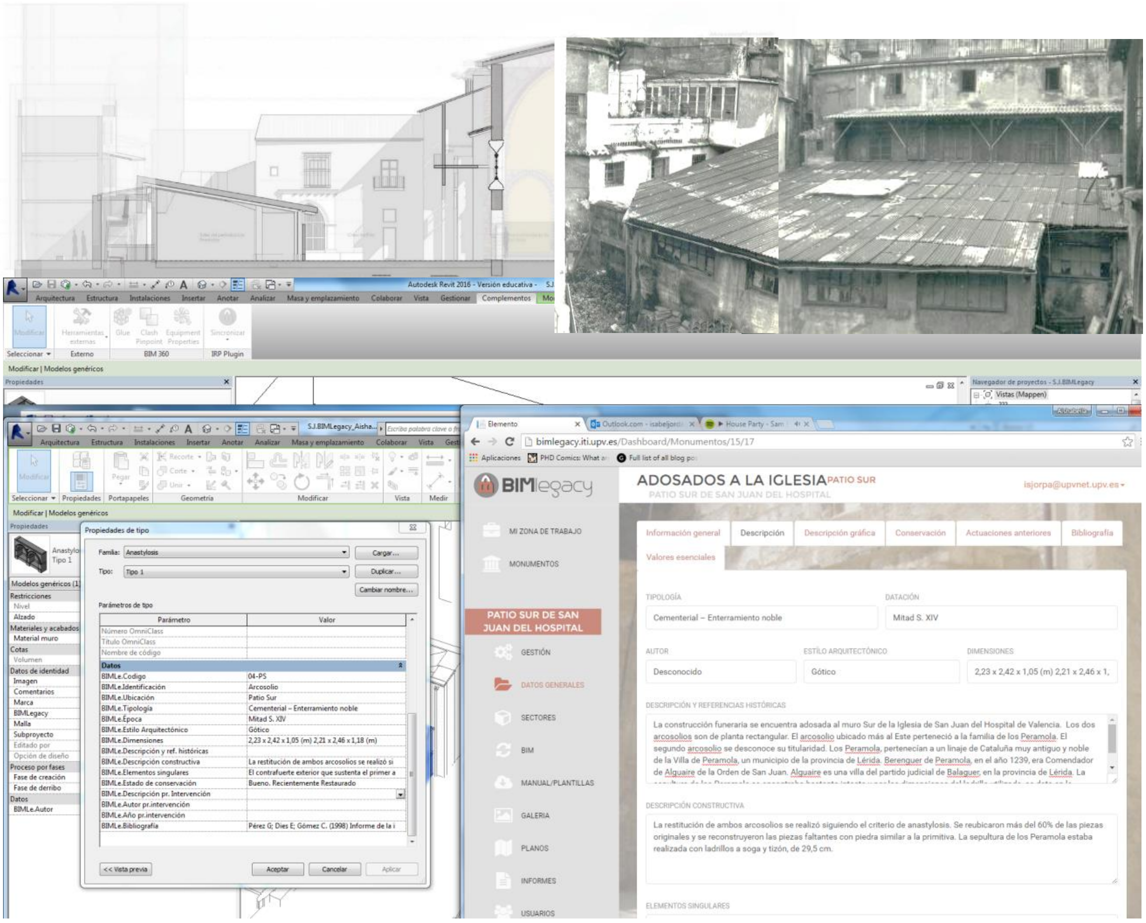


Figure 65. Synchronization between the HBIM model data and BIMlegacy data. Mr. Rubén March Oliver and Ms. Isabel Jordán Palomar. HAR2013-41614-R project (developed in Spanish). 2017.

Outputs of the model

The outputs of San Juan model were plans, schedules, and memories and the information linked in BIMlegacy platform. BIM software can naturally produce these kinds of outputs. In this project, a graphic annex was produced with plans, 3D views and axonometries from the HBIM model (Annex 2).

The views template was predefined in the BIMlegacy template, but it was completed and perfected within San Juan project. The quality of the graphics was optimised through the tool “modify graphics in the view”. Textures and colours were added to the graphics to improve the project quality, according to the conclusions of the workshop in Huddersfield, the previous case study that were considered to design BIMlegacy protocol-2.

Clash detection

Order and class detection are essential in any BIM project. Thus, a clash detection of San Juan model was performed. The criteria list was comprised: the correct use of categories, the parametrisation order and nomenclature, the limitations of the model, the intersections between different disciplines modelling, which means the architecture was confronted against MandE systems, and archaeology was confronted against architecture to check if there were any incompatible elements. The clash detection between different disciplines was easier to check since each discipline was modelled in their own subproject. Running the clash detection scan or report brought up some duplicate instances of the same issue. The BIM manager performed this clash detection using Revit clash detection tool and Navisworks to specifically check the systems.

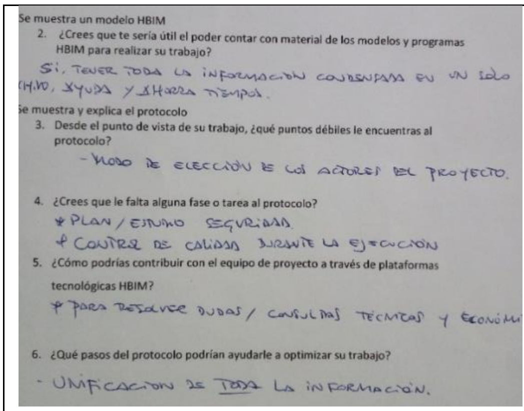
4.2.4.6 Interviews to San Juan stakeholders

BIMlegacy protocol-2 and platform and its application to San Juan case study were evaluated in the different semi structured interviews. These interviews lasted between one and two hours after signing the participant consent form for scientific projects of the University of Huddersfield. The interviews were carried out with the following stakeholders:

- The director of San Juan, industrial engineer, doctor in theology, rector of the church, 3 years of experience.
- The computer graphics manager, cultural diffusion, Degree in Advertising and Public Relations, 3 years of experience in San Juan and more years in similar work.
- The director of the museum, artistic manager, Professor of Drawing, degree in Fine Arts, 25 years of experience.
- The tourist guide of San Juan, art historian, 15 years of experience as a volunteer.
- The heritage inspector, Doctor architect, 12 years of experience as governmental heritage supervisor.
- The urbanism architect, 17 years of experience, 5 years working in heritage projects.
- The maintenance technician, former construction worker, 7 years of experience.
- The contractor, technical architect, 20 years of experience.

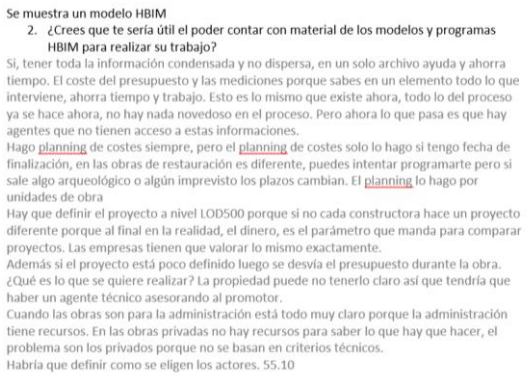
The interviews were divided into three parts. In the first part the stakeholders were asked about their daily life and their relationship with other stakeholders. The second part treated about HBIM methodology and three-dimensional models applied to heritage. The third part was an evaluation of BIMlegacy protocol with questions such as: What weak points are in the protocol? What steps of the protocol could help to optimise your work?

Almost all interviews were recorded, after the explicit approval of the participants. Then the audios were literally transcribed (Figure 67) and complemented with handwritten notes taken during the interviews, Figure 66. The idea was identifying the similarities between different interviews and the stakeholders' suggestions to further improve the protocol and platform.



Se muestra un modelo HBIM
2. ¿Crees que te sería útil el poder contar con material de los modelos y programas HBIM para realizar su trabajo?
Sí, tener toda la información condensada en un solo (H.M), ayuda y ahorra tiempo.
Se muestra y explica el protocolo
3. Desde el punto de vista de su trabajo, ¿qué puntos débiles le encuentras al protocolo?
- Modo de elección de los actores del proyecto.
4. ¿Crees que le falta alguna fase o tarea al protocolo?
* Plan / Estudio seguridad
* Control de calidad durante la ejecución
5. ¿Cómo podrías contribuir con el equipo de proyecto a través de plataformas tecnológicas HBIM?
* Para resolver dudas / consultas técnicas y económi[cas]
6. ¿Qué pasos del protocolo podrían ayudarle a optimizar su trabajo?
- Unificación de toda la información.

Figure 66. Notes taken during the interviews, 2017.



Se muestra un modelo HBIM
2. ¿Crees que te sería útil el poder contar con material de los modelos y programas HBIM para realizar su trabajo?
Si, tener toda la información condensada y no dispersa, en un solo archivo ayuda y ahorra tiempo. El coste del presupuesto y las mediciones porque sabes en un elemento todo lo que interviene, ahorra tiempo y trabajo. Esto es lo mismo que existe ahora, todo lo del proceso ya se hace ahora, no hay nada novedoso en el proceso. Pero ahora lo que pasa es que hay agentes que no tienen acceso a estas informaciones.
Hago planning de costes siempre, pero el planning de costes solo lo hago si tengo fecha de finalización, en las obras de restauración es diferente, puedes intentar programarte pero si sale algo arqueológico o algún imprevisto los plazos cambian. El planning lo hago por unidades de obra
Hay que definir el proyecto a nivel LOD500 porque si no cada constructora hace un proyecto diferente porque al final en la realidad, el dinero, es el parámetro que manda para comparar proyectos. Las empresas tienen que valorar lo mismo exactamente.
Además si el proyecto está poco definido luego se desvía el presupuesto durante la obra.
¿Qué es lo que se quiere realizar? La propiedad puede no tenerlo claro así que tendría que haber un agente técnico asesorando al promotor.
Cuando las obras son para la administración está todo muy claro porque la administración tiene recursos. En las obras privadas no hay recursos para saber lo que hay que hacer, el problema son los privados porque no se basan en criterios técnicos.
Habría que definir como se eligen los actores. 55.10

Figure 67. Transcriptions of the interviews, 2017

The transcriptions of the interviews were analysed with the scientific software Nvivo, specially designed to analyse data obtained in interviews, the data obtained in the interviews was analysed and the common points between the transcripts sentences were codified, Figure 68.

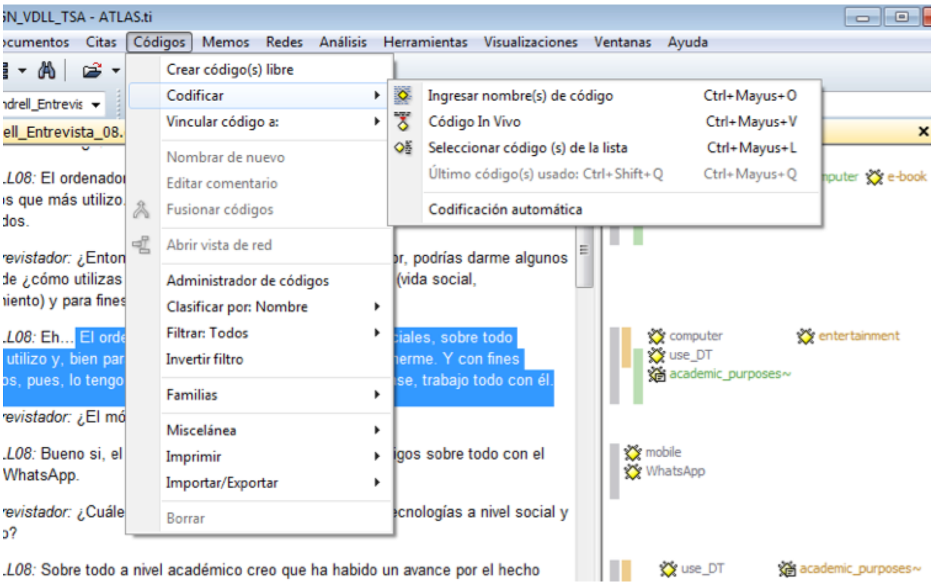


Figure 68. Analysis of the interviews with the scientific program Nvivo, 2017.

The analysis of this organised data facilitates the comparison of conclusions, which allowed to further improve both BIMlegacy protocol-2 and platform.

4.2.4.7 *C*onclusions and recommendations

The experience gained in San Juan case study helped to improve BIMlegacy protocol-2 by identifying possible issues related to BIMlegacy protocol practical implementation. Some important heritage processes, such the archaeology report relationship with the HBIM historic and constructive phases, and the wide variety of stakeholder's backgrounds, are examples of findings through this case study.

Conclusions of San Juan Case study

San Juan case study results were very useful to apply and evaluate BIMlegacy protocol-2 because it facilitated the understanding of the heritage stakeholders' tasks and necessities, modelling and documentation HBIM has been successfully developed and the evaluation of the protocol has been performed with San Juan stakeholders.

- BIMlegacy protocol and platform helped non-technical stakeholders to be active within the HBIM process.
- BIMlegacy protocol and platform unified the information and the unification of the information reduced errors. It helped the distribution of information or the disconnection between the works of heritage stakeholders.
- The benefits of BIMlegacy adoption was the reduction of project time dedication and the improvement in the project quality due to the accuracy of the data that was synchronised within BIMlegacy and the non-duplication of information. The unification of data linked in BIMlegacy on a single model demonstrated very good results. BIMlegacy helped to order and unify the amount of dispersed information that the case studies accumulated among the centuries.
- BIMlegacy protocol and platform reduced the project time dedication and improved the project quality.
- The modelling guidance offered in BIMlegacy protocol reduced the time-consuming process of modelling.
- HBIM historical phases had a great potential for the monument's cultural dissemination.
- BIMlegacy protocol and platform promoted the cultural diffusion of San Juan within local communities and society.

This knowledge was used to further improve BIMlegacy protocol-2 to its third version. There is an increase in demand within the industry for heritage stakeholders who want to adopt HBIM methodology and this protocol and platform will help heritage groups to implement HBIM.

Recommendations for San Juan

San Juan benefits from using the BIMlegacy protocol because it makes the preservation and cultural diffusion of the monument more efficient and supports the collaboration between interdisciplinary stakeholders.

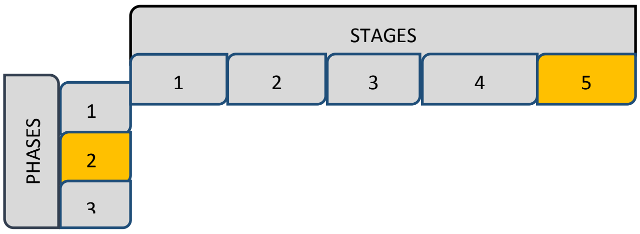
An "as built" HBIM model of San Juan will be beneficial because it will unify the historic-artistic, archaeologic, architectonic, maintenance, and structural condition information. Projects of similar monuments in England and Belgium have had very good results (Arayici *et al.*, 2017; Boeykens *et al.*, 2012)

HBIM models are very flexible in relation with historic hypothesis, which will be an important improvement in San Juan. These recreations of historic hypothesis can be used for cultural broadcasting and touristic reclaim within the general public and with the scientific and academic public. As an example, the HBIM model developed in the Sta. María in Scaria d'Intelvi was used for cultural dissemination (Brumana *et al.*, 2013).

It is recommended to use the HBIM model to manage and schedule future interventions in San Juan and to have more control over the costs and timescale of the construction works, as is indicated by Miglinskas in their studies of the benefits and issues of BIM (Migilinskas *et al.*, 2013).

The benefits of BIMlegacy adoption by San Juan work group was the reduction of project time dedication and the improvement in the project quality due to the accuracy of the data that was synchronised within BIMlegacy and the non-duplication of information.

4.2.5 FOCUS GROUP TO EVALUATE BIMLEGACY PROTOCOL AND PLATFORM-2



BIMlegacy protocol and platform-2 were presented in a focus group with external interdisciplinary participants to evaluate and validate its effectiveness and efficiency. This focus group were performed with members of the Grupo de Usuarios de Revit de Valencia (GURV) after checking their profiles and sending the assistance invitations (see Figure 69). The focus group started with a presentation of the protocol, platform and project results (see Figure 70).

Figure 69. Focus group informative poster, 2017.

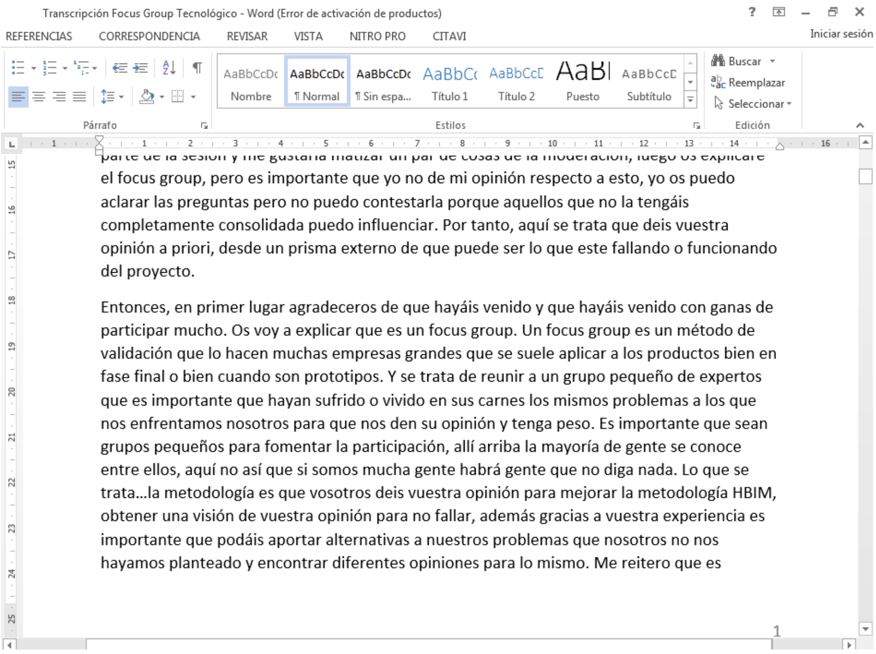
The focus group participants were:

- BIM consultant (6 years of experience)
- Architect, BIM university professor with knowledge of heritage architecture (18 years)
- BIM modeller, specialist in HBIM (3 years of experience)
- BIM specialist is a construction engineer (4 years)
- BIM architect with experience in heritage (25 years)
- Planning consultant who uses BIM (10 years)
- Construction manager with experience in BIM (6 years)
- Heritage broadcaster, architect (20 years of experience)

Figure 70. Picture taken during the focus group presentation, 2017.

The participants were divided into two groups after the initial presentation, the more technical participants and the methodological participants in order to contrast their opinions in a more valuable way. All of them validated the overall protocol and platform together.

This focus group was recorded, and the conversations were transcript and analysed following the same process that in previous evaluations.



parte de la sesión y me gustaría matizar un par de cosas de la moderación, luego os explicaré el focus group, pero es importante que yo no de mi opinión respecto a esto, yo os puedo aclarar las preguntas pero no puedo contestarla porque aquellos que no la tengáis completamente consolidada puedo influenciar. Por tanto, aquí se trata que deis vuestra opinión a priori, desde un prisma externo de que puede ser lo que este fallando o funcionando del proyecto.

Entonces, en primer lugar agradeceros de que hayáis venido y que hayáis venido con ganas de participar mucho. Os voy a explicar que es un focus group. Un focus group es un método de validación que lo hacen muchas empresas grandes que se suele aplicar a los productos bien en fase final o bien cuando son prototipos. Y se trata de reunir a un grupo pequeño de expertos que es importante que hayan sufrido o vivido en sus carnes los mismos problemas a los que nos enfrentamos nosotros para que nos den su opinión y tenga peso. Es importante que sean grupos pequeños para fomentar la participación, allí arriba la mayoría de gente se conoce entre ellos, aquí no así que si somos mucha gente habrá gente que no diga nada. Lo que se trata...la metodología es que vosotros deis vuestra opinión para mejorar la metodología HBIM, obtener una visión de vuestra opinión para no fallar, además gracias a vuestra experiencia es importante que podáis aportar alternativas a nuestros problemas que nosotros no nos hayamos planteado y encontrar diferentes opiniones para lo mismo. Me reitero que es

Figure 71. Literal transcription of the focus group, 2017.

As a result, the following recommendations were listed:

Recommendations to improve BIMlegacy protocol-2

- The application of the protocol in common heritage buildings must be progressive; it is not realistic to think that it can be totally applied since the lack of knowledge and BIM culture of heritage stakeholders.

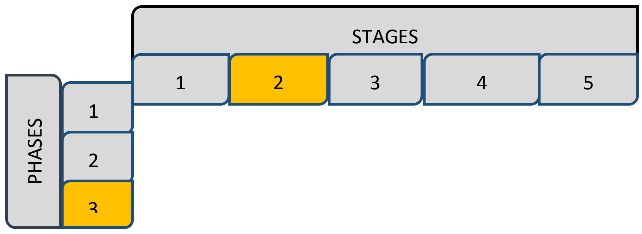
- The feedback of the protocol users is extremely important, so it is proposed to be archived in the BIMlegacy protocol.
- Different participants in the focus group had pointed that the stakeholders that could maintain the HBIM model are: (1) the architect, they could maintain the HBIM model under contract requirement, as any other professional task; (2) the contractor, even as requirement to participate in any project, as it is required to maintain a building, an HBIM model can be asked to maintain and updated; (3) the administration, to warn the cleaning company, maintenance, MandE systems revisions. However, in the use phase, the administration almost does not participate.
- The archivist must include the historic-artistic information in BIMlegacy platform.
- It is beneficial that the heritage inspectors participate within Step 0. Asset intervention strategy. Heritage projects are so complex that a closer inspector revision is beneficial.
- It is proposed to add a work constructions agenda in BIMlegacy. In heritage buildings, where visitors, and people is using the building when the construction phase, it is important to know exactly who will work in the monument each day, what materials and vehicles are going to access to the site, etc.
- It is proposed to add a digital agenda in the BIMlegacy web platform to manage the logistics, visits, and meetings in the monument.
- It is proposed to add an application to monitoring governmental economic support in BIMlegacy, their public calls, and requirements to be aware of any public foundation.
- A possible future line or research could be the translation of technical HBIM models to a visual language for generic tourists. For that, it is necessary to define what models will be of interest to the visitors, for example, how to easily browse the model.
- Another use of HBIM models could be to transmit to the authorities and support foundations the values of the monument so they can have more options to gain economical support.

Recommendations to improve BIMlegacy platform

- BIMlegacy prototype platform was considered valid and achieved the main issues identified within the literature review. However, as a technological tool, the focus group participants explained that the technology of the platform should be constantly updated.
- BIMlegacy platform was tested in one project, San Juan, but more case studies and heritage groups should prove it to further test it. The platform is a novel technological tool, so with further testing in future projects, its quality and utility will improve considerably.
- It was proposed to add a visor in BIMlegacy website. BIMlegacy platform does not incorporate a visor, currently it only has alphanumeric fields. Some focus group participants pointed out that the platform will be more intuitive if it could have a visor of the project directly in the website.
- Even though not-technical stakeholders considered that the platform functioning is intuitive and simple, it was identified that it is likely that these stakeholders would require a level of HBIM training to understand how to work with BIMlegacy and HBIM models.

4.3 PHASE 3

Phase 3 started with the definition of objectives after San Juan case study and the evaluation of BIMlegacy protocol-2 and BIMlegacy platform. The specific objectives of phase 3 were to complete BIMlegacy protocol-2 and correct the processes that resulted unsatisfactory in the previous phase.



4.3.1 CHANGES PERFORMED BETWEEN BIMLEGACY PROTOCOL 2 AND 3

The focus group was recorded, transcribed and analysed with the scientific tool N-vivo (10 Annex 3. Qualitative data analysis using Nvivo), and a list of changes was listed to improve BIMlegacy protocol-2:

- BIMlegacy protocol-3 is much more developed than BIMlegacy protocol-2, it is basically its evolution. New layers of the protocol were required to further explain the protocol.
- It was required that BIMlegacy protocol-2 clearly defines the responsibility of the stakeholders in step 0. *Asset intervention assets*. It is a basic requirement to know the criteria of the work assignation to other stakeholders.
- The LOD in Step 3. *Develop the design for the intervention* must be very high, LOD 500, because the project must be much defined, so the different contractors can budget the same budget items and the budgets comparison can be easily done.
- It was necessary to add the following processes in Step 4. *Planning the physical intervention*: generating of the Health and Safety Plan, quality control, and security coordination.
- Step 8 of the BIMlegacy protocol-2 required an extra task that was the generation of graphics to promote cultural diffusion and touristic signs to help visitors to locate and evaluate what they are seeing.
- Step 2. *Determine intervention options*, needed to be completed with the task: determination of the options for iconic constructions in the monument. Projects in the very iconic monuments cannot be assigned without doing a previous public tender because they suppose a historic contribution even though they are privately owned.
- The Health and Safety study must be done within BIMlegacy protocol; each project unity must be linked to associate risks and preventive actions, probably added in the budget lines and not necessarily in the HBIM model.

<u>BIMlegacy protocol-3: design process</u>

To further complete and develop BIMlegacy protocol-2 to version 3, principles and processes of ICOMOS were overlapped with the existing protocol, (Antonopoulou and Bryan, 2017), Figure 72.

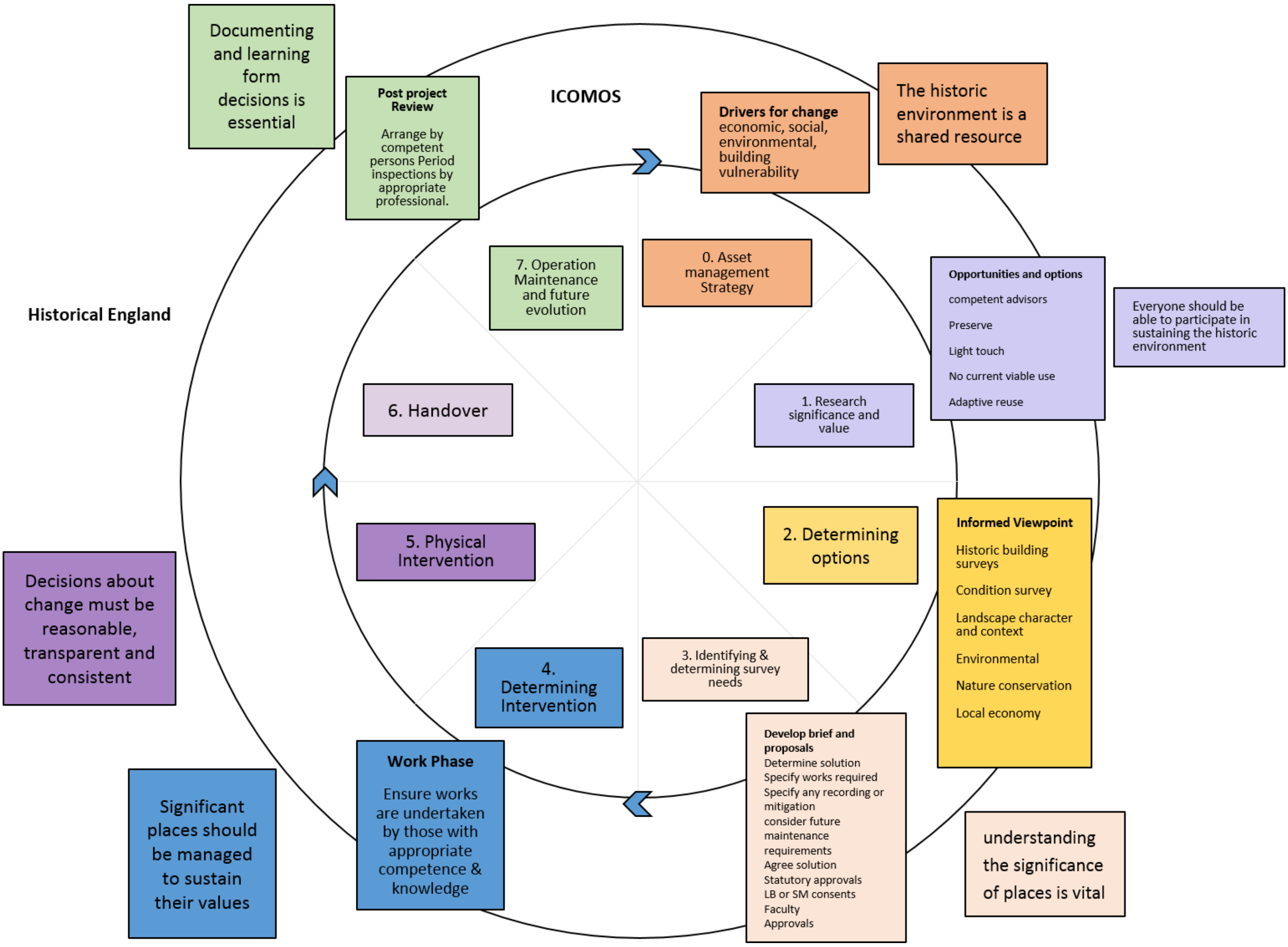


Figure 72. Grouping of ideas relating the literature review findings. In the diagram Historical England principles are summarised and grouping with ICOMOS principles. (Antonopoulou and Bryan, 2017).

The Conservation Principles of Historical England had been taken into account as well as the ICOMOS Education and Training Guidelines (Maxwell, 2014). Historical England criteria and processes were also taken to complete certain processes and compared with step 2 of the investigation findings, Figure 73.

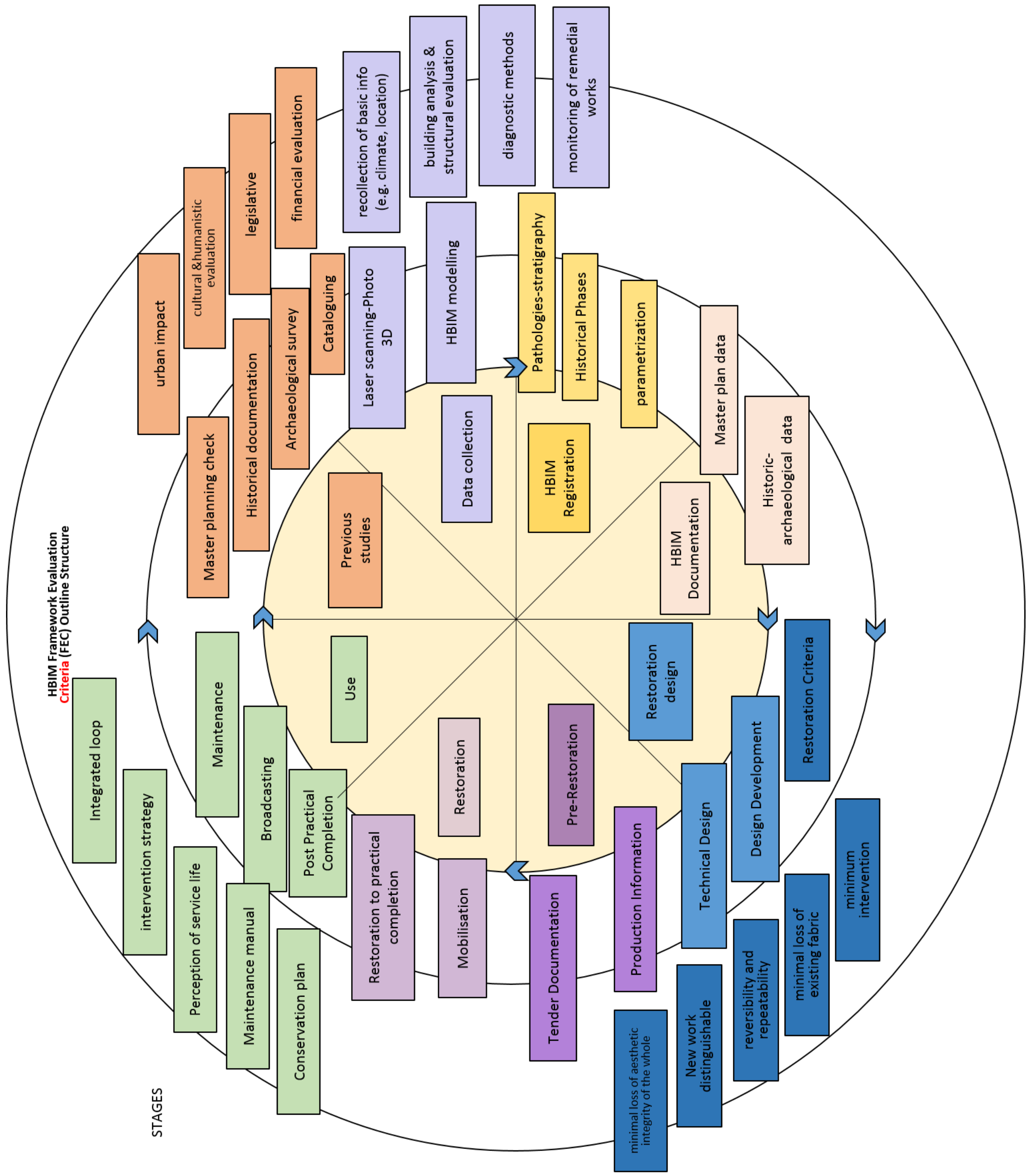


Figure 73. Work flowchart ordering processes and criteria from Historical England, 2017.

The tasks developed by each stakeholder were ordered by affinity with the principles of the COTAC Report. So, both diagrams Figure 72 and Figure 73 were overlapped.

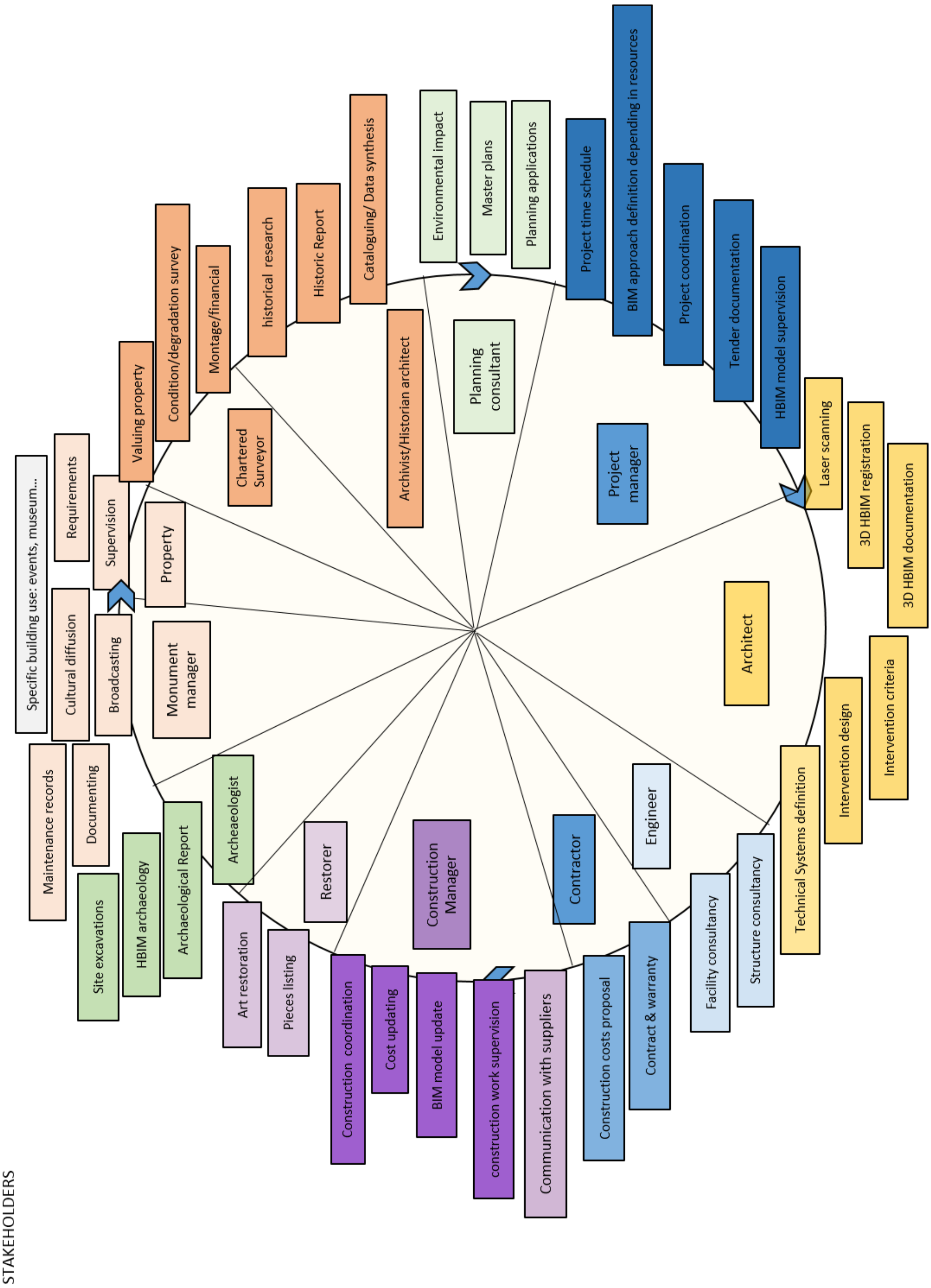
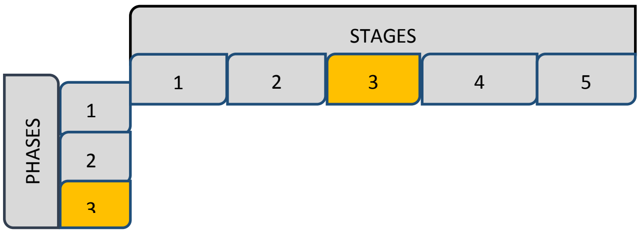


Figure 74. Work flowchart to order the tasks that each stakeholder develops, 2017.

With all these improvements, a new version of the protocol was developed, BIMlegacy protocol-3 that is one of the outputs of this doctoral thesis and is explained in further detail below.

4.3.2 BIMLEGACY PROTOCOL-3



4.3.2.1 General description

BIMlegacy protocol-3, shown in Figure 75, is an overall protocol to manage HBIM interventions during their life-cycle. BIMlegacy protocol, a result of this doctoral thesis, was presented in the paper named "Protocol to Manage Heritage-Building Interventions Using Heritage Building Information Modelling (HBIM)", published in Sustainability the 21st of March 2018 (Jordan-Palomar *et al.*, 2018).

BIMlegacy protocol-3 was developed on the basis of the CIC BIM Cyclical Diagram, Construction Industry Council, (Antonopoulou and Bryan, 2017), as well as on the results of the primary data collected throughout these two previous steps of this investigation that consisted of Fixby Hall case study and San Juan case study.

It was divided into eight chronological steps and its structure is circular, having in the centre the BIM model and the BIM Platform. BIMlegacy protocol proposes that the intervention information should be hosted online, as heritage stakeholders usually do not work in the same physical space, this was the case in San Juan project. The communication between the HBIM models and the historians and archaeologists' databases were designed to be unified in real time. In this online space, stakeholders have a workspace to share data.

The definitive version, BIMlegacy protocol-3 included three layers of development–A, B and C–and each layer has a higher level of detail (Figure 75, Figure 76, and section 4.3.2.2 and 4.3.2.3).

Layer A was designed to be clearly understandable by all stakeholders (see Figure 75). It contains all the steps of the protocol accompanied by illustrative logotypes.

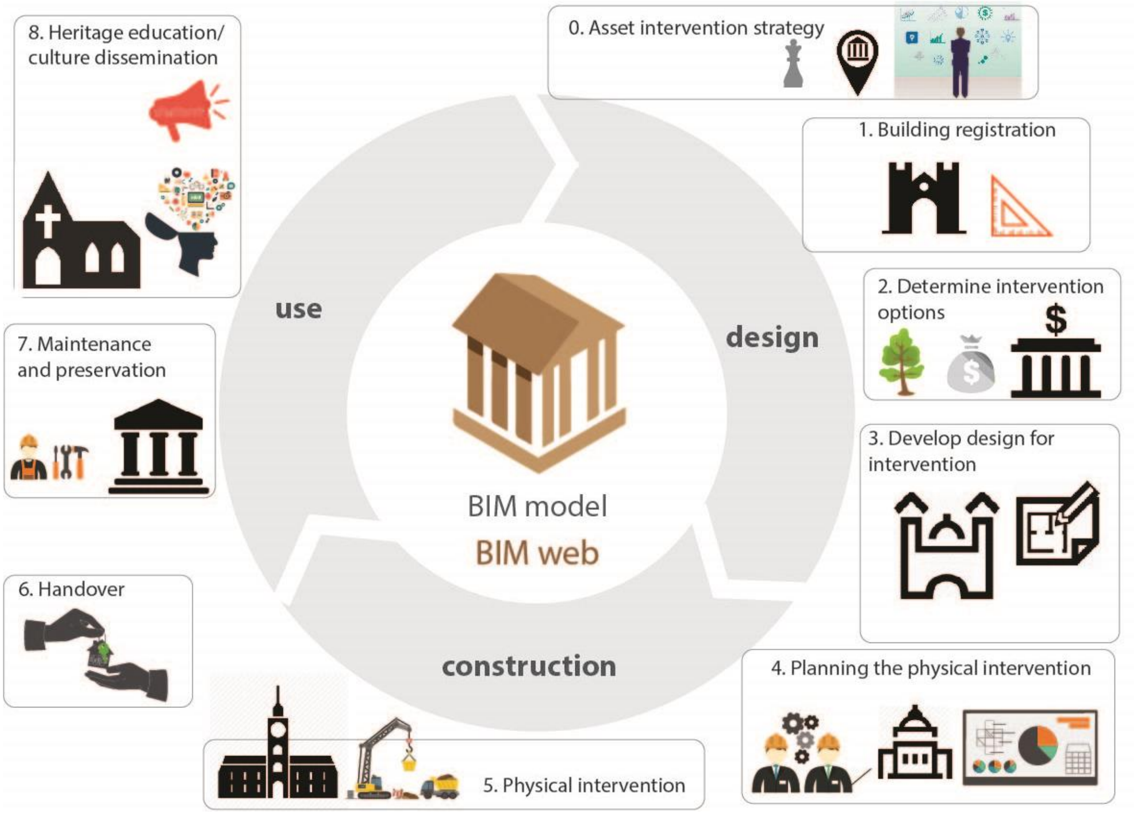


Figure 75. BIMlegacy protocol-3, layer A, 2018.

Layer B (Figure 76) contains all the activities of each step of the life cycle and it describes all the steps of the protocol. It consists of eight pages, each of which describes the different steps of the process. It is also designed to be clearly understandable by both technical and non-technical stakeholders describing who should participate and who leads the step, and there is a task-list with a concise description of each one.

Figure 76. BIMlegacy-3, layer B, 2018.

Layer C (section 4.3.2.2 and 4.3.2.3) includes a modelling protocol and HBIM guides with specific explanations for each of the eight steps of BIMlegacy protocol. Its focus will be to support the technical teams who were leading each step. It will include: (1) how to develop HBEPS, (2) the heritage template, (3) a guide of LOD in HBIM, (4) instructions on how to perform the general modelling, (5) a guide on how to build HBIM parametrised families, such as pointy arcs, and (6) how to model sculptures within HBIM. Not all the guides of all the steps have been developed within this doctoral thesis, thus, future lines of research can be to develop such parts. For example, the ongoing doctoral thesis of Mr. Elena Salvador García develops the use stage of the protocol specifically step 8. Heritage education and cultural dissemination.

BIMlegacy proposes specific training for heritage stakeholders: owner, planning consultant, chartered surveyor, historian, archaeologist, monument manager, planning officer prior, architect, engineers, contractor, suppliers, construction manager, construction workers, and restorer. It is a well-known fact that architects, engineers, and construction companies are starting to use BIM (Zhao *et al.*, 2015). However, heritage stakeholders have in general poor BIM knowledge, so those projects cannot yet achieve the intended benefits from HBIM. Specifically, the non-designer stakeholders require training to understand the technology potential to start to develop their activities in a HBIM environment. It is believed that this will represent a significant improvement in the heritage production chain as it is corroborated by the work developed by Holzer who has been working with non-technical BIM users achieving very good results (2016). This concept could be named "HBIM for the property". As building owners have no previous technical knowledge, HBIM for the property needs to be as much user-friendly as possible. So, the online platform proposed in this research where non-technical stakeholder can link data with the HBIM models is considered very useful due to its visual interfaces and simplicity (Jordán-Palomar, I., García-Valldecabres, J., 2018).

These eight steps are comparable with the life-cycle management methods such as RIBA Outline Plan of Work (RIBA – Royal Institute of British Architects, 2007), and Building Smart Spanish Chapter (Building SMART Spanish Chapter, 2014b) as is explained in section 3.3 Research Design. The differences between BIMlegacy and previous protocols in the literature (Figure 3, Figure 4) are:

- It includes the breakdown of each step, which previous protocols, figure 1 y 2, did not have.
- It provides the indicative LOD that each step should have.
- It includes specific processes of interventions in historical buildings, such as the representation of pathologies in step 1, the definition of the historical evolution of the building in step 1, and the engagement of the community with heritage using HBIM as graphical resource in step 8.
- It modifies some standardised BIM tasks to adapt these to historical architecture activities. For example, the modelling of archaeological remains and the inclusion of heritage values within the HBIM model parameters.
- It also includes specific stakeholders such as the restorer, the archaeologist, the charter surveyor or the archivist, and their relationships with the HBIM procedures.

4.3.2.2 Description of the steps of BIMlegacy protocol

Step 0. Asset intervention strategy, Figure 77, includes (a) the general exploration of the building –its first visit, photography report, and general measurements–; the understanding of the client's brief in relation with the buildings previous studies – unlike new construction historical buildings require previous studies and a documentation project before doing the intervention project–; (b) the definition of the contract between the property and the project team (a.e. architect, archaeologist, and archivist) to develop the registration step; (c) the identification of the building's significance, its antiquity, artistic values, and cultural meaning; (d) the monetary value of the building; (e) the research of the historical and archaeological records; (f) the valuation of the property; (g) the consultation of the master plans; and (h) the definition of the BIM Execution Plan (BEP), which will manage the HBIM procedure.

The strategy step is more extensive than in regular projects because heritage buildings usually require detailed previous studies of the architectonic, historic, and archaeological values of the building (Naeyer *et al.*, 2000). Furthermore, the establishment of a Common Data Environment (CDE) is key to enable data sharing throughout the intervention project. The level of development (LOD) recommended for this phase is LOD 100, and only an initial HBIM model with BIM masses is helpful since it is just required to obtain general measurements, and to archive the initial information. The need for an intervention strategy was established with the basis of existing protocols (e.g. COTAC, 2016). Such need was also validated by the stakeholders in the validation workshop performed in Huddersfield (section 4.1.7).

Figure 77. BIMlegacy, layer C, specific approach 0. Step 0. Asset intervention strategy, 2018.

The HBEP must be defined in this step. This contractual document must define the objectives of the project, the human and material resources, the interchange file format, the legal owner of the HBIM model, and the steps and necessities of the heritage project.

BIMlegacy describes all the stages of a heritage building intervention; nevertheless, not all projects will require such detailed modelling and the requirements for each project should be defined at the beginning of the process, according to the strategic objectives of the client and the project members' abilities with BIM. How HBIM is going to be implemented at each specific step must be defined in step 0.

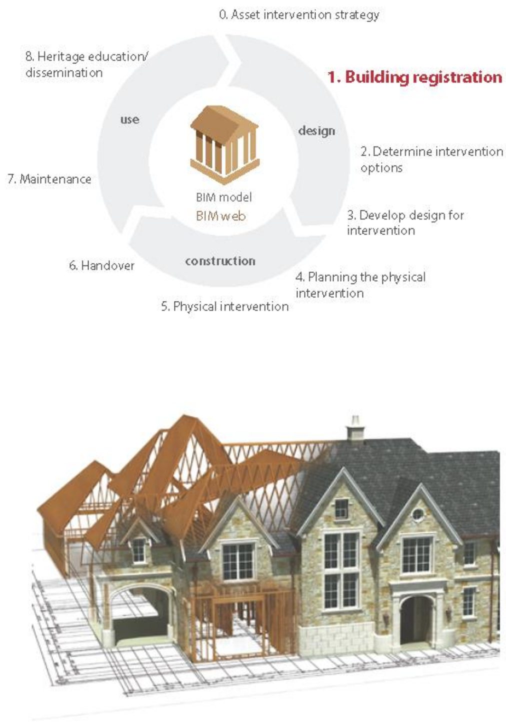
Step 1. Building registration consists of the architectonic survey and the link of all the historical, archaeological, and city planning information, Figure 78. The 3D modelling takes the point cloud from laser-scanners as a skeleton to start the model. The HBIM modelling of the building includes the generation of HBIM materials and building details (detailed construction drawings) libraries as well as HBIM families with specific and repetitive stylistic elements.

Modelling the current degradation condition of the building embraces the pathology's representation and the stratigraphic studies representation if necessary. In addition, it includes the MandE modelling, the structure modelling, and the artistic sculptures modelling. The building registration must be at least LOD 200, but the modelling of the existing condition should have a LOD 300 level of detail since the point cloud provides accurate information and it is the most relevant construction step.

The **archaeological modelling** is important not just to document the archaeological remains but also to generate the evolutional hypothesis of the asset.

This step also contemplates the definition of its **historic evolution** with specific guidance for the levels of detail of the different historic hypotheses of the building. This means that it is representing not just the building nowadays but documenting and representing how it was at different periods in the past. This links with the idea that heritage buildings documentation should have cultural documents as well as a useful construction model. BIMlegacy defines different levels of development (LOD) for the constructive hypothesis in HBIM depending on the available data (a.e. old drawings of the building, ancient descriptions of the building), for the specific historic phase represented. This is a real necessity of HBIM modelling according to the literature (Department for Communities and Local Government of United Kingdom, 2012). For example, it is required to model the XII century phase in a Church but there is not enough information to model it with LOD300. This guide defines the LOD depending on the available information defining each historical phase.

By using BIMlegacy, the **documentation** of relevant historic and archaeological data would be unified due to the possibility of representing different historical phases in one single HBIM model and having the online platform associated, which has all historical, cultural and archaeological information (Naeyer *et al.*, 2000). This step describes a complete heritage architectonic project; nevertheless, not all projects will require such detailed modelling since it depends on the models' purpose defined in step 0.



1. Building registration

Architect/ project manager/ archivist/ chartered surveyor/monument manager/archaeologist

Historic evolution definition_ project manager/ archivist
-Define which historical phases need to be represented in the 3D model.

HBIM building survey. Architecture modelling_architect/ project manager/archaeologist
0. Architectonic laser scanner survey. Some alternatives are photogrammetry or traditional survey.
1. 3D modelling of the surroundings (generic) and the existing phase of the building (great detail).
2. Model the archaeological remains in a linked archaeological 3D model.
3. 3D HBIM modelling of the previous historic-constructive phases of the building.
4. Generate the BIM families by standardizing the constructive elements that are repetitive in these types of buildings.

Modelling the material records_architect/ chartered surveyor
-Analyse the building's material and document the HBIM model with the material details of the different parts of the building.

Modelling the Degradation/condition details_architect/ chartered surveyor
-Analyse the buildings condition and report the degradation problems. Document the HBIM model after.

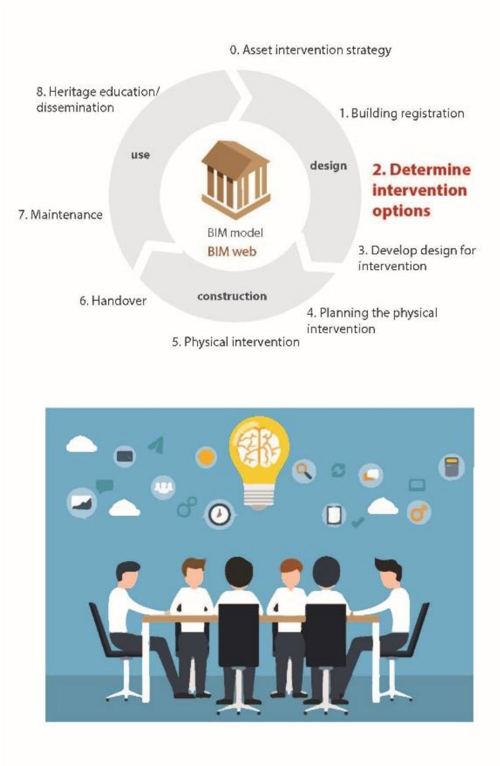
M&E modelling and structure modelling_architect/engineer
These 3D models of existing facilities and existing structure may be linked with the architectonic model.

HBIM documentation_planning consultant/chartered surveyor/archivist/ project manager
-Link the models to relevant information such as historic, archaeologic, mainteinance records archived by the property and any information related with the condition of the structure and the condition of the facilities.

Figure 78. BIMlegacy, layer C, specific approach 1, 2018.

<u>Step 2.</u> Determining intervention options of the possible refurbishment, restoration or conservation of the building entails an overall evaluation of the building and/or site, Figure 79. The definition of the intervention criteria considers both the project design criteria and the construction criteria, for example the type of concrete to be used or the decision of excavating the foundations manually. This requirement's list provided by the client will be more specific than the previous client brief of step 0. By now, the client will have all the information of the building's registration. BIMlegacy plays the role of unifying information in this step enabling the stakeholder's functional communication through the HBIM platform. The LOD should continue in LOD 200 for previous historical phases and LOD 300 for the existing phase.

This general evaluation aims to contemplate all the relevant aspects for the future intervention: the consultation of the legislative frame; the preliminary cost estimation; operational issues, environmental, and economic studies. After this evaluation and after the laborious 3D HBIM modelling process developed in the previous step, the definition of the intervention criteria and the client's requirements listing for the asset's intervention project would be much more coherent because of the large amount of elaborate information available to perform the decision making.



2. Determine intervention options

Project manager/ property/chartered surveyor/planning consultant/Architect/ contractor

Legislative parameters_ planning consultant

-Know the legislative frame in order to plan a suitable intervention in four levels: international, national, regional and local.
-These will require consultations with the City Hall planning and heritage departments.

Preliminary cost estimation/ budget definition_ contractor/ project management/ property

Definition of the project budget

Consider future maintentace_project manager/ architect/ planning consultant

-Study the intervention strategy taking into account the maintenance and sustainability of the building.

Environmental impact_project manager/ planning consultant

-Research about the environmental impact of the future intervention. -Study the integration of the intervention in the existing landscape.

Economic impact_chartered surveyor/ project manager

-The use given to the building needs to be economically sustainable to secure appropriate building's maintenance and conservation.

Intervention criteria_architect/ project manager/ property

-Establish the intervention criteria after studying the different conservation, restoration and rehabilitation criteria according to the international and national principles and laws (e.g. ICOMOS, Historic England).

Define procurement_project manager/ property

Ideally this would be an Integrated project delivery.
Definiton of the pre-contractual BEP.

Client requirement management_project manager/ property

Review the initial client requirements and adapt them to the possible intervention options.

Figure 79. BIMlegacy, layer C, specific approach 2, 2018.

Step 3. Developing design for intervention includes the conservation, restoration or refurbishment project itself and its documentation, Figure 80. It includes the assignment of work to different stakeholders, the intervention project's design with a guide of LOD, the constructive project, the statutory approvals managing, and the development of the structural and MandE project. Ideally different interdisciplinary stakeholders will work in the 3D models in real time with different permissions depending on the case. Designs may be developed using 3D models as base to produce the intervention project. Different stakeholders may work with the 3D models. Architects, archaeologist, and construction engineers would model in separated areas or sub-projects of the 3D file or even in different files linked by specific coordinates. HBIM Energy consumptions 4D simulations should be performed in this step to ensure the right sustainability behaviour of the heritage building. At the end of the step, a design HBIM model with a LOD 400 should be produced.

Currently the tender documentation is generally required in paper format and it is not common to allow HBIM models to support statutory approvals. However, BIMlegacy is designed to end up delivering HBIM models to the government's authorities. BIMlegacy proposes the supervision of intervention projects for the unification and transparency of the system.

Figure 80. BIMlegacy, layer C, specific approach 3, 2018.

Step 1 to 3 were established with the experience achieved performing Patio Sur case study and completing it with the existing literature review. Then these steps were validated and completed in the focus group with heritage professionals.

Step 4. Planning the physical intervention (see Figure 81). This scheduling must consider specific regulations of the restoration field and it must consider uncertainties of an ancient building (e.g. unexpected structural damages, humidity in internal surfaces). The construction stakeholders in collaboration with the design and property stakeholders would lead this step. HBIM will be used to develop a 4D 'as built' construction model with a LOD 500. Every HBIM element may be linked with its actual cost item within specific software for construction cost calculation (a.e. arquimedes from Cype, Presto). The construction plan is developed in specific 4D BIM software. Clash detection should be performed in this step to reduce conflicts during the building intervention.

Thus, Step 4 addresses the cost estimation, the economical budget, the construction planning, timing adjustments, and the synchronisation with the sub-contractors that also includes restorers and archaeologists. HBIM will be used to develop a 4D 'as built' construction model with a LOD 500, almost the maximum level of development, in order to recreate the real intervention in the heritage asset beforehand. These operations require the HBIM platform due to the synchronisation of data in real time. The construction planning is developed in a specific BIM software to create a virtual reality HBIM model.

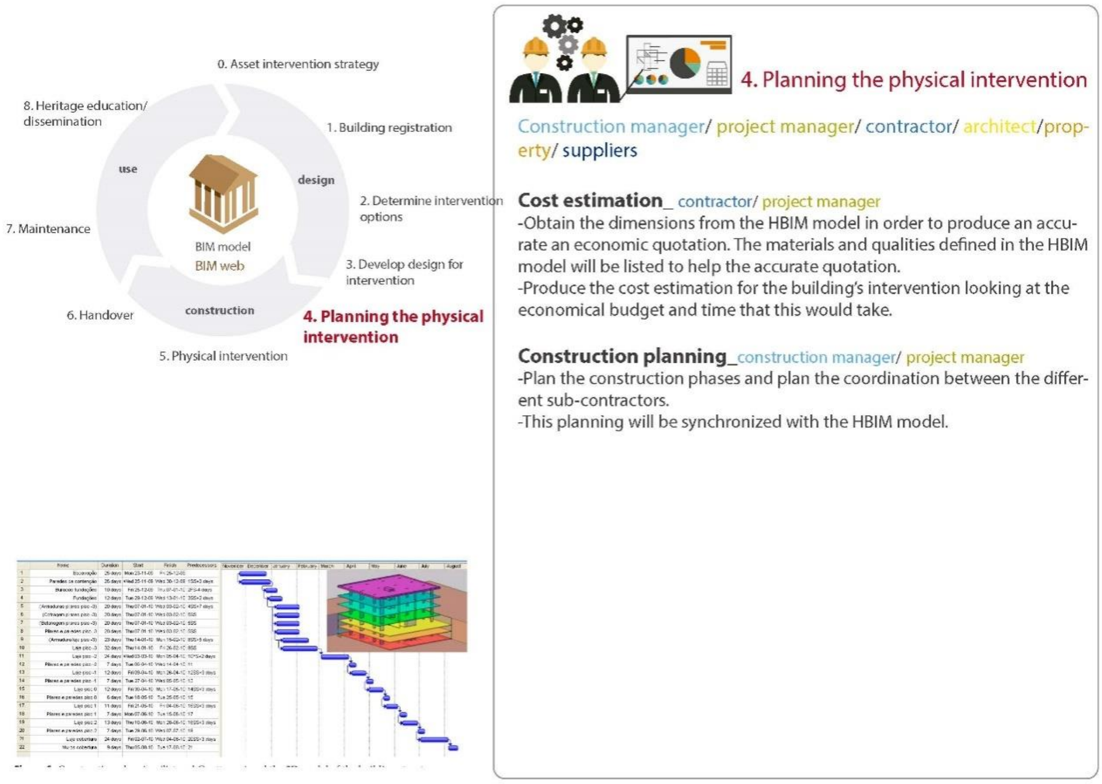


Figure 81. BIMlegacy, layer C, specific approach 4, 2018.

<u>Step 5</u>. Physical intervention (see Figure 82). Historical buildings usually need specific materials and constructive techniques to retain their integrity and to avoid producing unwanted chemical reactions (Naeyer *et al.*, 2000). During this step an ‘as built’ HBIM model will be developed based on information collected during construction. The LOD should be 500 to provide the necessary level of detail.

This step addresses the planning time delivery, which means the coordination of the different sub-contractors; the operations on the construction site following the restoration regulations; costs control during the construction works; the health and safety plan; the HBIM documentation during the building’s construction. It would be necessary to add constructive techniques data, materials data, supplier’s data, in order to preserve heritage legacy as source of historic information; and the construction quality checking. Clash detection should be performed in this step to reduce conflicts during the building intervention. Ideally, the HBIM as built construction model will change at the same time as the real construction goes because the construction manager will periodically update the HBIM model on site with the possible changes using devices such as tablets or smartphones. Visual HBIM platforms where the HBIM models will be held will foster the collaboration between these stakeholders in real time, the BIM360 from Autodesk Company for example.

Figure 82. BIMlegacy, layer C, specific approach 5, 2018.

Step 6. Handover (see Figure 83). It addresses the warranty and contract review and allows the team to meet and learn from decisions that have been made. In this step the team may expose the intervention problems and discuss solutions for further projects. The transparency promoted through BIMlegacy facilitates the understanding of the stakeholders' issues. For example, all stakeholders could check the HBIM final construction model to see the final measurements. The technical stakeholders would access the HBIM model through BIM architectonic and engineering software whilst non-technical stakeholders would access it through the online platform and its simple viewer. At the end of this step the HBIM model 'as built' should be delivered to the legal owner who was previously defined in the HBEP.

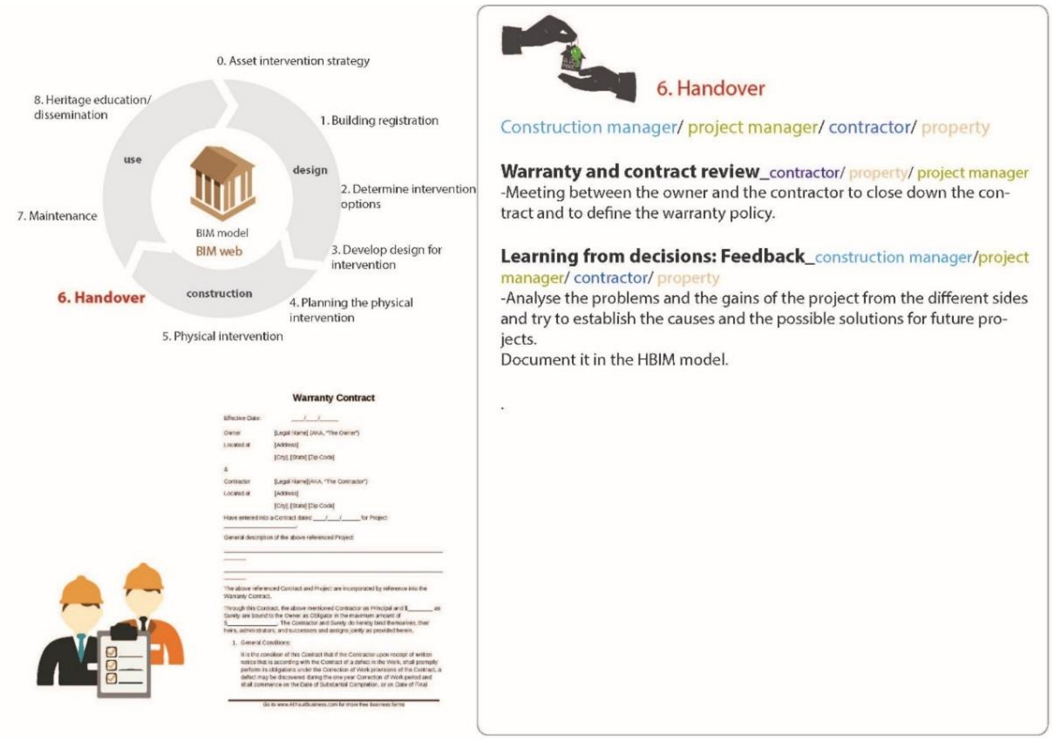


Figure 83. BIMlegacy, layer C, specific approach 6, 2018.

Steps 4 to 6 elements were designed with the findings from the Fixby Hall case study, specifically with their last refurbishment. Then these steps were completed with the analysis of similar case studies in the literature, and evaluated with the stakeholders who participated in the workshop.

Step 7. Maintenance (see Figure 84) details the schedule of the preventive maintenance, assessing energy efficiency, the environmental policy awareness, and the maintenance and documentation control through the 'as built' model. Historic buildings require special attention to maintain their facilities and to preserve their cultural and artistic values. The 'as built' model is a fundamental aspect in HBIM maintenance, but the research results show that maintenance managers of historic buildings demand a simple system to control maintenance and not complex software. Thus, incorporating maintenance information to the HBIM model and linking it to the specific management system that the property uses is essential. If the 'as built model' is too complex or it has too much information, it will not be useful for maintenance managers. In addition, BIMlegacy proposes to control the renting process and the furniture inventory through online platforms, but this is a future line of study.

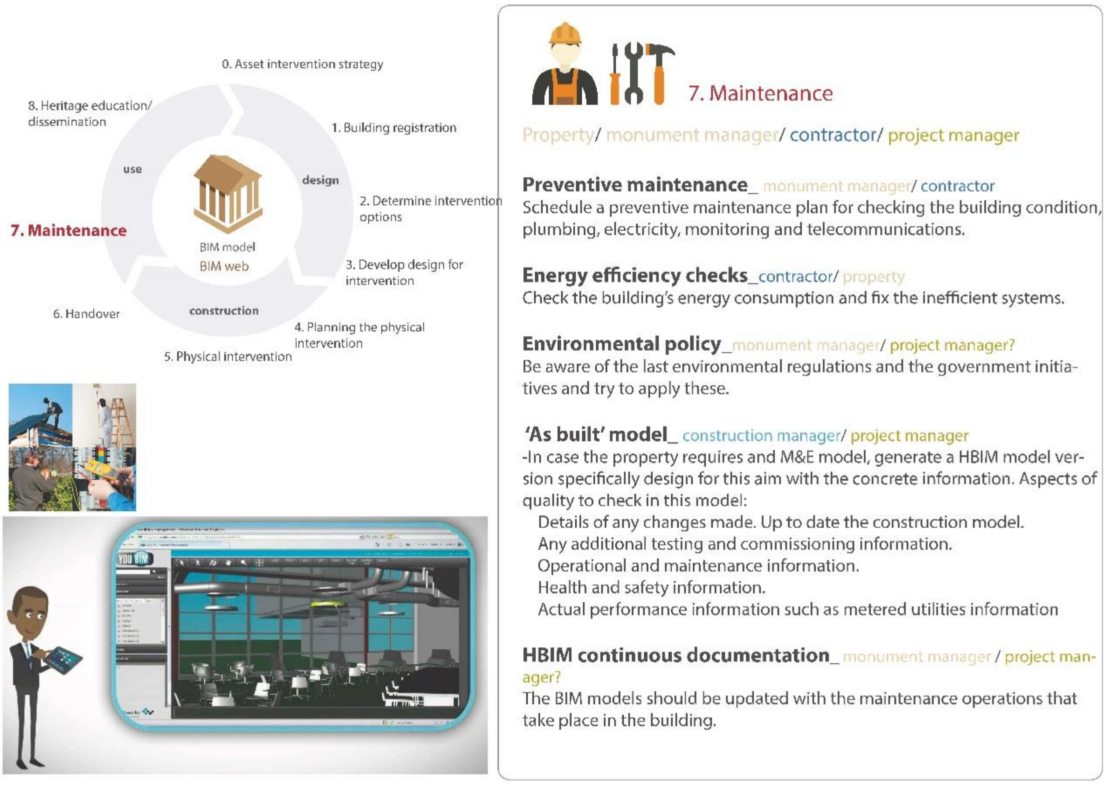


Figure 84. BIMlegacy, layer C, specific approach 7, 2018.

Step 8. Heritage education (see Figure 85). This step involves the community engagement, the cultural dissemination, the education in terms of preservation of historic sites, and the identification of funding bids and government grants.

Heritage buildings usually have a rich history that makes them suitable as iconic community locations or touristic sites. This step contemplates the integration of those intrinsic heritage processes within BIMlegacy. It proposes to use HBIM models as source of data to better explain the architecture legacy to the potential visitors. BIMlegacy proposes to manage the public visit control, the divulgation of the cultural values of the building within the community, and the positioning as cultural site within the protocol.

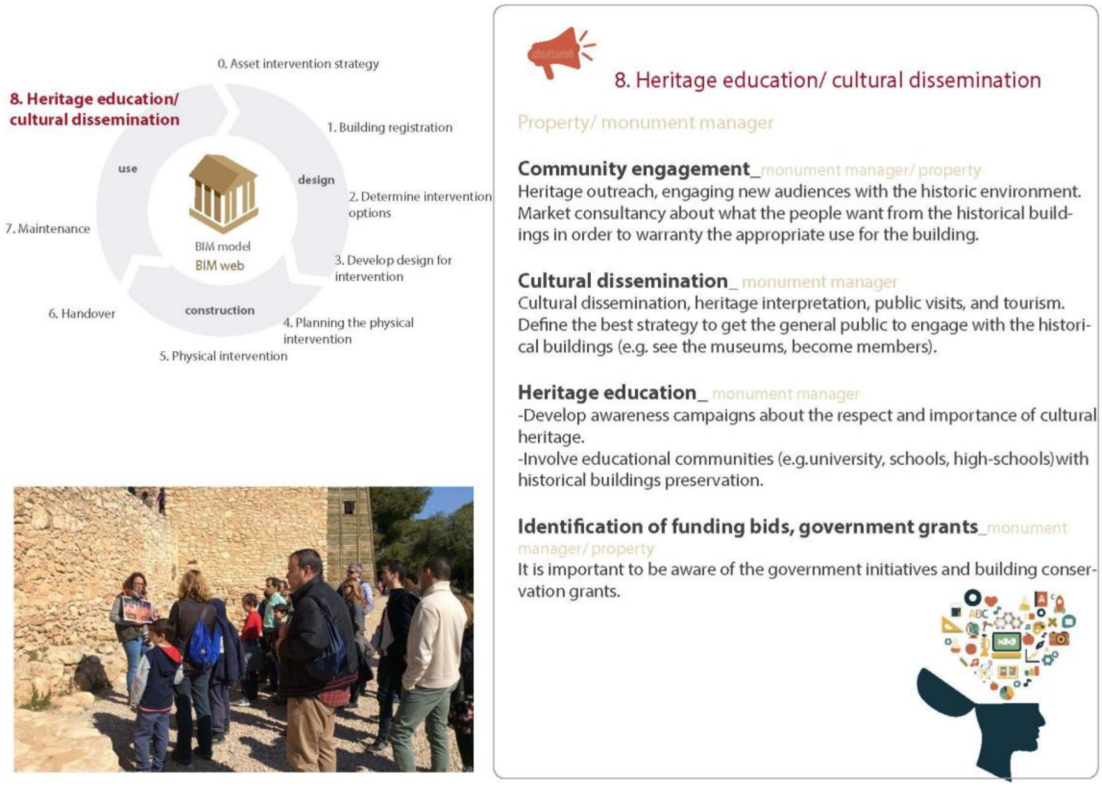


Figure 85. BIMlegacy, layer C, specific approach 8, 2018.

Step 7 and 8 steps were established after analysing the maintenance and heritage dissemination of all the monuments analysed in this research. These elements were validated in the workshop performed in Fixby Hall.

4.3.2.3 BIMlegacy layer C

Some steps of the protocol were further developed with greater detail level. This layer of the protocol aims to help technical heritage stakeholders in their HBIM projects. They contemplate technical aspects that are not resolved according to the literature.

It includes: (1) how to develop HBEPS, (2) the heritage template, (3) a guide of LOD in HBIM, (4) instructions on how to perform the general modelling, (5) a guide on how to build HBIM parametrised families, such as pointy arcs, and (6) how to model sculptures within HBIM.

This guidance to BIMlegacy protocol-3-layer C was designed to keep developing further aspects of the protocol that require specific guidance to help heritage groups.

Heritage BEP

Step 0 of BIMlegacy protocol *Strategy* was further developed to create a BIM Execution Plan (BEP) specifically designed for heritage buildings. It was needed since it does not exist according to the literature review (Dore and Murphy, 2017). This part of the research was developed within Mr. Gustavo Heredia’s master final project which was supervised by Ms. Isabel Jordán and Prof. Jorge García Valldecabres. The development of such a plan, for facilitating the management of information in a HBIM project, is set out in PAS 1192-2:2013 BS

EN ISO 19650 where it is defined as a "plan prepared by the suppliers to explain how the information modelling aspects of a project will be carried out".

The most used terminology of BEP is BIM Execution Plan, which is adopted by international institutions such as The University of Georgia Tech and Pirncenton, “The construction Users Roundtable”, Building Information Modelling Task Group, the MIT, and the Building Management Plan (Mora, 2015). The plan, often abbreviated as BEP or BxP, is developed both pre- and post- contract and is prepared as a direct response to the Employer's Information Requirements (EIR). The BEP will detail the project deliverables stipulated by the contract and the information exchange requirements detailed in a BIM protocol, such as the CIC BIM Protocol (a supplementary legal agreement that is incorporated into construction and professional services contracts via a simple amendment).

An HBIM project requires a BIM Execution Plan (BEP) that in a heritage project is a strategic document to achieve objective, to line up processes, resources, and stakeholders (The Construction Users Roundtable, CURT, 2010). There is not any heritage BEP template to guide the HBIM projects. To develop a HBEP template it is important to know the objectives of the HBIM project, in order to detect the necessary BIM uses to apply.

BEPs are a tactical and strategic tool to planning the interaction between the HBIM team from the beginning of the project and the contract until the maintenance phase, going through design and construction. Some organisations such as the CPIc (Construction Project Information Committee) of United Kingdom have published a generic pre-contractual BEP template that can be easily adapted to the specific project. However, it is recommended to complete and improve the BEP of each team or company with the experience achieved in previous projects. The BEP should not be isolated of the general programming and objectives of the project. The “BIM Project Execution Planning Guide V. 2.0” stands the scope of the BIM implementation and affirms that the BIM plan must be developed within the first stages of the project and it should be constantly updated, reviewed, and approved. BEP has two parts, the pre-contractual, which behaves as solicitation document; and the post-contractual, that is an operative planning. Pre-contractual BEP is developed before contracting the teams, thus, there are a lot of unknown details. The post-contractual BEP is an extension of the pre-contractual BEP after all the project stakeholders are formally part of the project and realistic resources are known. The goal of a post contractual is to adjust the expectations and the right assignations of resources within a BIM project in order to achieve the objectives on time and with quality.

According to different sources, the parts of a BEP are described in the Cambridge document that summarised previous BEPs such as the Georgia Tech (2016) and the Saluja (2009) (University of Cambridge, 2016). As these guides recommend, this BEP guide started by asking what aspects should be covered. There were lots to consider when it comes to determining how information is managed, planned for and documented, what standard methods and procedures were used to deliver the information. The considerations were:

- The BEP should include agreed roles and responsibilities (and relevant authorities and approval processes), a strategy for key deliverables and what existing information will be used, and a guide to the key project milestones and where these fit as part of the wider programme.
- The logistics of collaborative processes (including modelling) should be laid out with clear responsibilities. A revised Project Implementation Plan (PIP).
- Task Information Delivery Plan (TIDP) - showing responsibility for delivery of each supplier's information - and Master Information Delivery Plan (MIDP) - setting out when project information is to be prepared (by whom and using what protocols and procedures) was also needed.
- The BEP should also detail working procedure. How will BIM volumes be managed and maintained? What file name conventions will be adopted? What construction tolerances set and what attribute data required? A common approach to annotation, abbreviations and symbols were also required to avoid potential ambiguity. It was needed to determine what software was used, what data formats were used for exchange and what other data management systems were brought into play.

The Construction Project Information Committee, which is responsible for providing best practice guidance on the content, form, and preparation of construction production information (CPI), and making sure this best practice is disseminated throughout the UK construction industry, provided a BEP template, which has the contents shows in Figure 86.

Contents

Figure 86. BEP contents according to the Construction Project Information Committee, 2016.

Different BEPs were analysed and compared to create the HBIM template. For example Figure 86 is the Construction Project Information Committee proposal of BEP contents. This BEP template was used as reference. This guide was used to design a scheme to develop a HBEP as well as HBIM uses. This work was coordinated by Mr. Gustavo Heredia in its master's final project and supervised by Ms. Isabel Jordán Palomar and Prof. Jorge García Valldecabres. This work has been just developed in Spanish language. As a result, the HBIM uses proposed for the HBIM BEP were presented in Figure 87. The HBIM uses have been ordered by steps of the life cycle: preliminary studies, HBIM registration, HBIM documentation, design, pre-intervention, intervention, and use.

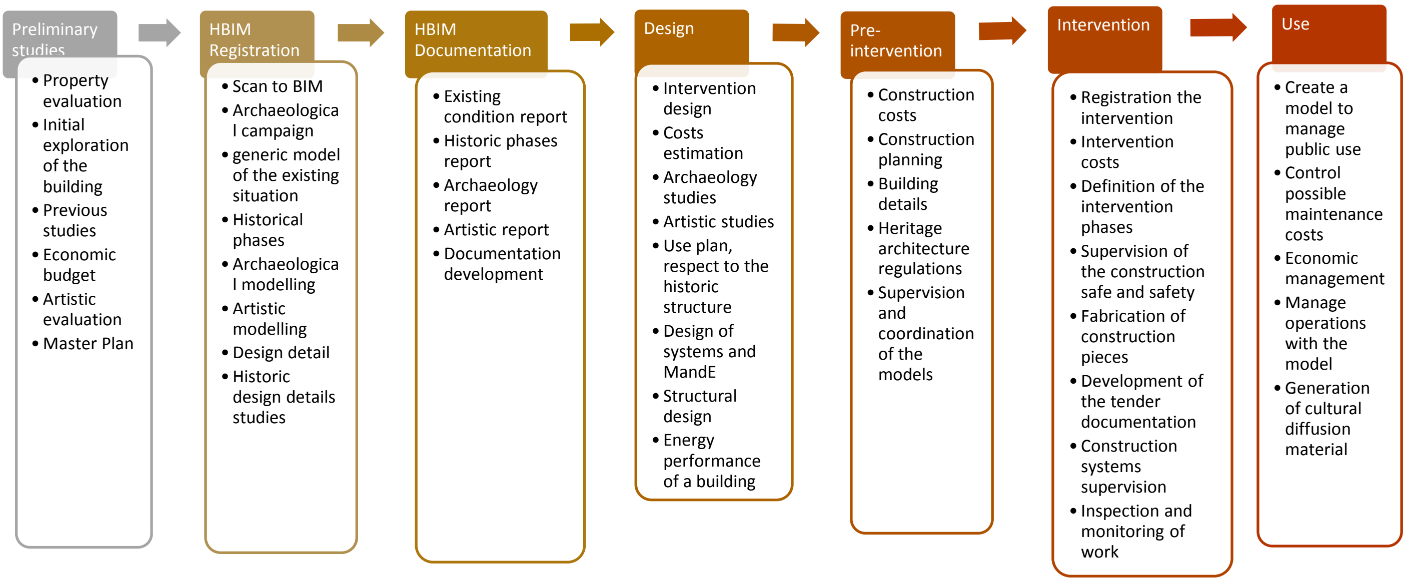


Figure 87. HBIM BEP of the BIMlegacy protocol-3, layer C, HBIM uses per step of the life cycle, 2018.

The HBIM uses need to be completed with the HBEP scheme per uses, processes, deliverables, and infrastructure. In order to complete the scheme per uses, other BEP examples were analysed such as Figure 88. BIM process timeline in design, construction, and post-construction stages. United-BIM, 2017.

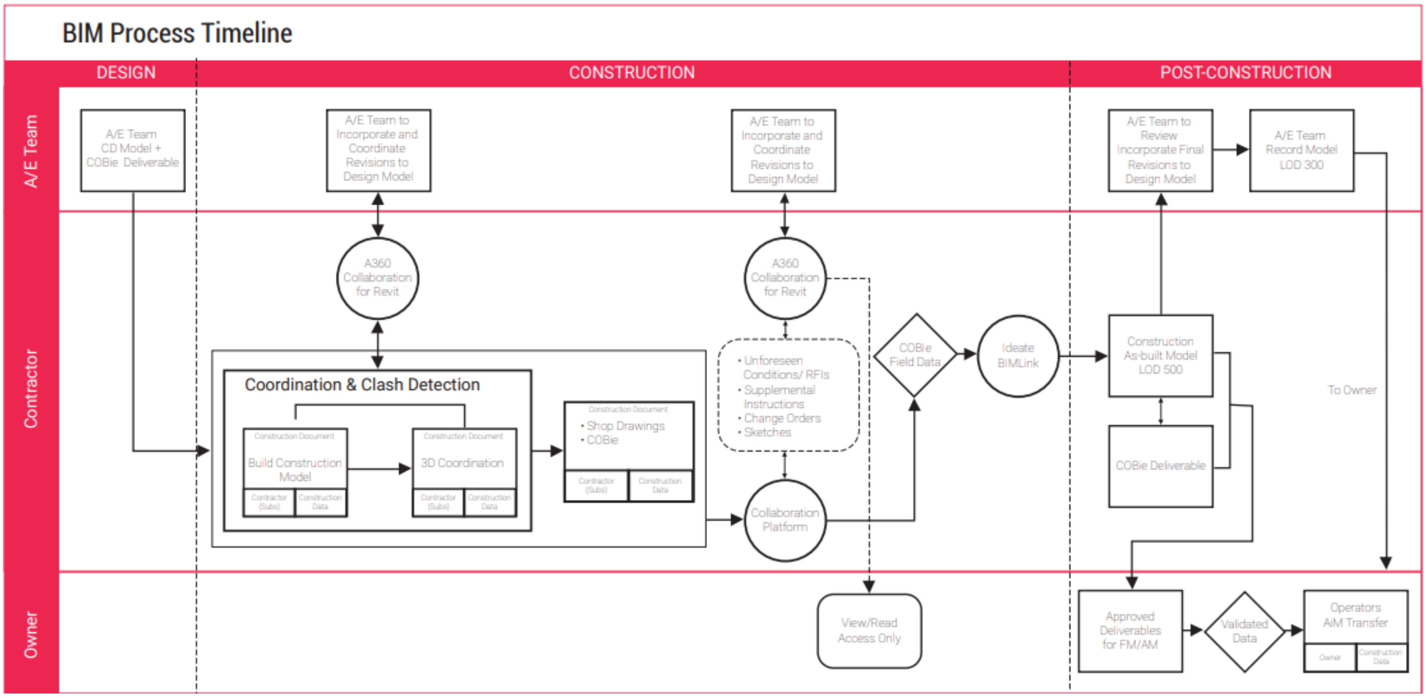


Figure 88. BIM process timeline in design, construction, and post-construction stages. United-BIM, 2017.

The developed HBIM template has multiple schemes to order the different uses. As an example of the template of HBEP developed in this research, Figure 89 contemplates the organisation of the HBIM for the uses part. This HBEP temple was developed in Spanish language like the BIMlegacy platform.

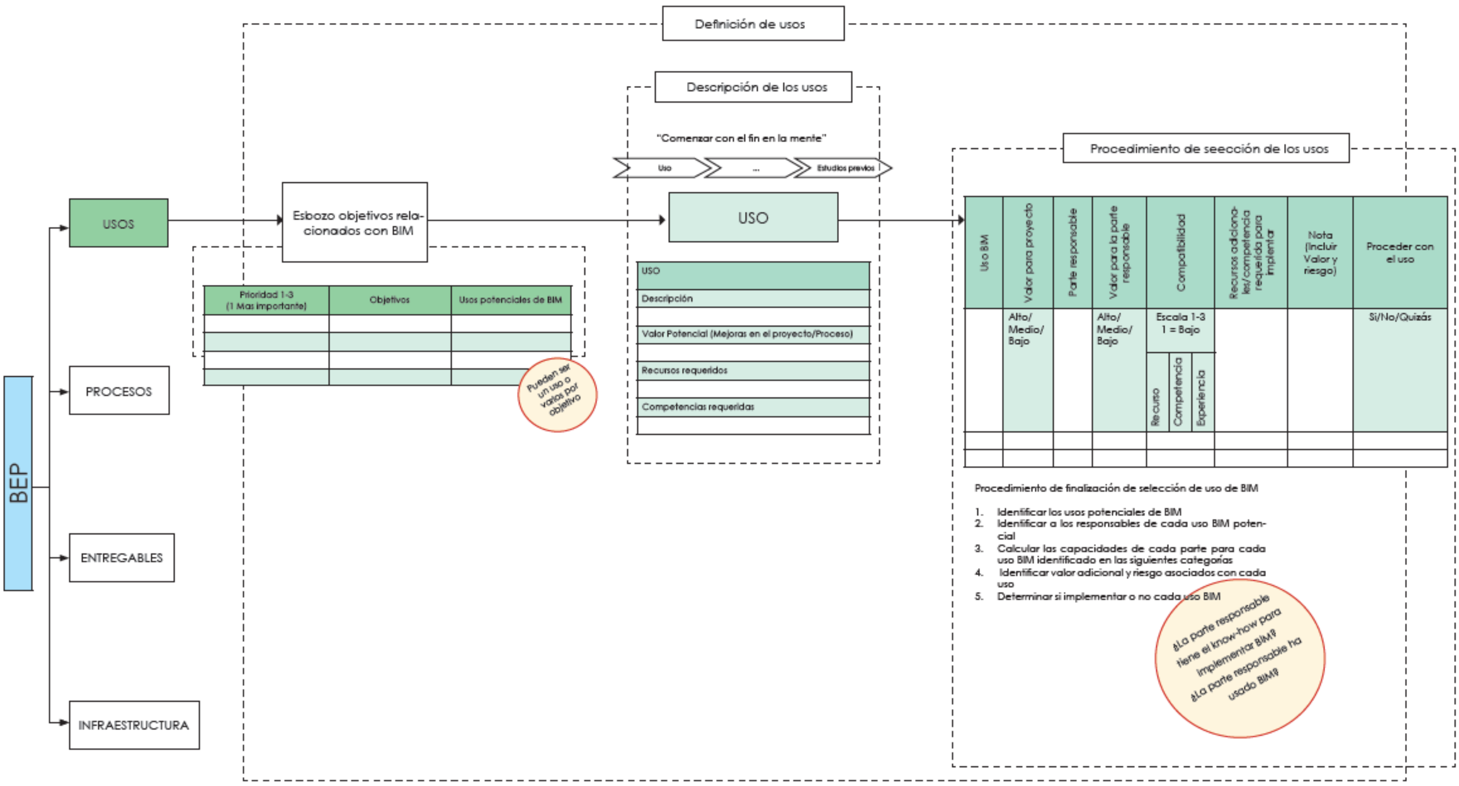


Figure 89. HBIM BEP of the BIMlegacy protocol-3, layer C, HBEP scheme per uses, processes, deliverables, and infrastructure. Heredia, 2017.

Heritage template

Templates are empty files that content all the families, standards, view templates, nomenclature system, prepared plans, and views organisers (Dore and Murphy, 2012). Templates usually are adapted to international standards such as ISO or DIN. Autodesk does not provide with a specific heritage template to start a new Revit project. There are just construction, architecture, structure, and systems templates.

It was necessary to design a BIMlegacy template containing all the heritage specificities in order to put it available in BIMlegacy platform so heritage groups that start to work with BIMlegacy and need a heritage template could use it to start a new project.

The heritage template was designed taking as reference previous HBIM templates used in the BIM personal professional experience. For example, the template used in Emma Create Architecten, developed during the time that the author of this document was working in Amsterdam, was used as reference (see Figure 90 and Figure 91).

Figure 90. HBIM project develop with an HBIM template developed during the time that the author of this document was working in Amsterdam, 2013.

Figure 91. HBIM project develop with an HBIM template developed during the time that the author of this document was working in Amsterdam, 2013.

BIMlegacy heritage template was designed within the BIMlegacy platform criteria and aiming to improve the workflow. Thus, a standardization of the characteristic elements of heritage buildings was done:

- Constructive phases as historic phases. In the BIMlegacy template, this Revit tool was adapted to represent the historic hypothesis of the heritage asset. This will help to represent previous restorations of the historical building.

- Detail groups adaptation to heritage detail groups. As for example, carpentry details, systems symbols, luminary symbols, and stratigraphy symbols.
- Constructive elements adaptation. Walls, ceilings, and desks were adapted to represent traditional heritage constructive elements, for example, using masonry, or restored wood desk.
- The creation of new materials. The default materials of Autodesk library are new construction materials. Thus, heritage materials such as masonry, lime, sand, adobe, were created and added to the BIMlegacy template.
- The heritage graphic style in Revit was created and added to the BIMlegacy template. Soft colours, complex line drawing was added, descriptive 3D to recreate historic hypothesis was added to the template.
- Heritage Revit families were created after an analysis and standardization of the repetitive patterns (a.e. gothic arcs, vaults, masonry pillars, Romanic doors).

This template was updated in BIMlegacy platform and it was used to start San Juan project.

The levels of Development (LOD) required technical definition

Level of development (LOD) is a concept with varying definitions and implementations. Core to the concept is that the level of development defines the content and reliability of BIM elements at different stages or milestones. “Content” means geometric information, structured data and linked documentation. “Reliability” means for what uses and to what extent the downstream users of the information can trust the accuracy and quality of that content (Fai and Rafeiro, 2014).

The LOD “classes” that are presented will, if correctly used, help to understand the usability and limitations of the modelled elements, Figure 92. And it is not just about the amount of granularity of information that has gone into a model. It is as much about the quality and trustworthiness of the information that can be extracted from the models (Fai and Rafeiro, 2014).

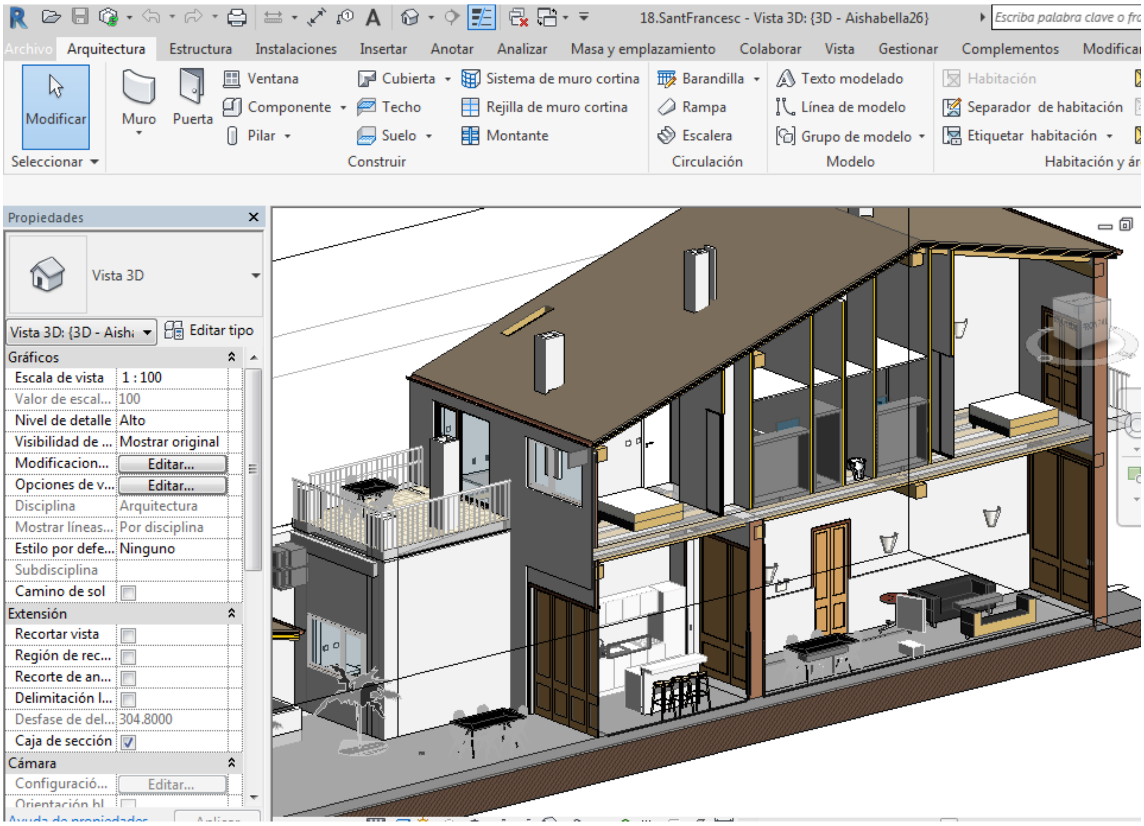


Figure 92. Example of BIM construction model with a high level of detail (Lod). 2017.

The LOD Specifications can be used in various ways. These can be used as attachments to contracts and as supplements to BIM Execution plans. They are also used as references in common standards to describe information management practices. There were not an specific definition of HBIM levels of development (Fai and Rafeiro, 2014), thus, HBIM LOD were defined as is detailed in the boxes below (Figure 93). It was developed within the final master's project of Mr. Roberto Mogena and supervised by the author of this doctoral thesis and Prof. Jorge García Valldecabres. This work was originally written in Spanish language, but the author of this thesis translated some figures in English, such as Figure 93 bellow:

LOD 100

It is a symbolic representation. Model elements or symbols show the existence of a component but not its shape, size, or precise location. Any information must be considered approximate. It represents 20% of the total amount information.

GRAPHIC INFORMATION

- Existence of the wall.
- Approximate location

NON-GRAPHIC INFORMATION

- Undetermined

LOD 200

It is a conceptual level and provides a general view with approximate dimensional information of the elements and its geometric definition. It represents 40% of the total amount of information.

GRAPHIC INFORMATION

- Existence of the wall.
- Units
- Thickness
- Approximately resigned

NON-GRAPHIC INFORMATION

- The typology of the elements must be indicated.

LOD 300

It is a generic level in which certain functions are already included. The element is defined graphically, specifying precisely the size, shape and location. It represents 60% of the total amount of information.

GRAPHIC INFORMATION

- Dimensions
- Units
- Thickness
- Layers
- Materials

NON-GRAPHIC INFORMATION

- Fabrication information of the elements or materials.
- Physical and chemical data

LOD 400

It is a specific level, the model have well-defined parameters in terms of size, shape, quantity and location, suitable to calculate cost analysis. It represents 80% of the total amount of information.

GRAPHIC INFORMATION

- Dimensions
- Materials
- Thickness
- Units
- Layers
- Amounts
- Vestiges

NON-GRAPHIC INFORMATION

- Fabrication information of the elements or materials.
- Physical and chemical data
- Guidance in detail
- Installation information
- Cost

Figure 93. Level of Development for HBIM. Idea suggested by Pr. Jorge García Valldecabres to Mr. Roberto Mogena and corrected by Ms. Isabel Jordán Palomar, 2018.

General modelling

To perform the general modelling with the right order it was considered as very useful to have a brief guide. This was one of the suggestions of the focus group participants (4.2.5 Focus group to evaluate BIMlegacy protocol and platform-2). These were the steps to follow when starting a HBIM model, Figure 94.

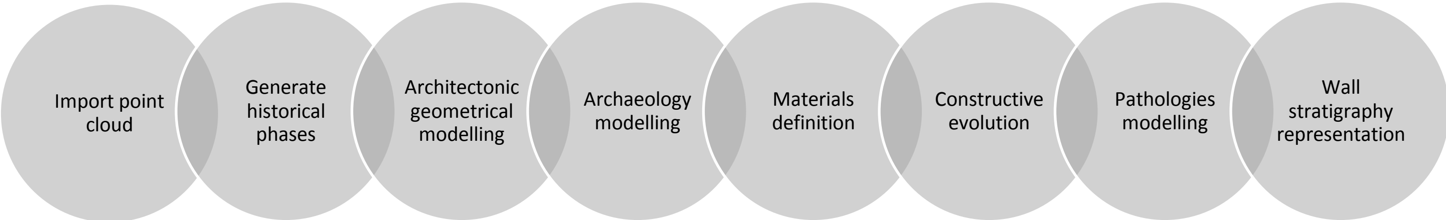


Figure 94. BIMlegacy protocol-3, layer C, guide to perform the general modelling, 2017.

1. Import point cloud
2. Generate historical phases
3. Architectonic geometrical modelling
4. Archaeology modelling
5. Materials definition
6. Constructive evolution
7. Pathologies modelling
8. Wall stratigraphy representation

Ideally this order should be followed when modelling in order to not have modelling issues or difficulties. General modelling gives as a result HBIM models with the in situ families (a.e. walls, floors, roofs) in the such as is showed in Figure 95, which is the general modelling of San Juan case study.

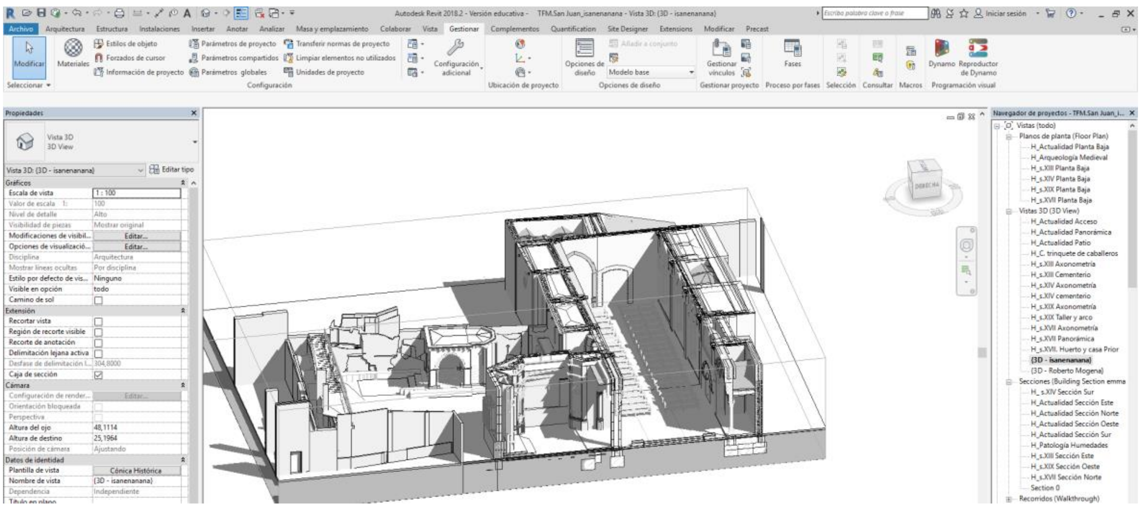


Figure 95. General modelling of San Juan case study. 2017.

Guide to model heritage parametric families

HBIM families are fundamental to develop an HBIM model since each constructive element has a practical, constructive, and compositional function within a building. HBIM families are part of the specific modelling that usually belongs to step 1 of BIMlegacy protocol. The specific modelling takes place after the general modelling.

The specific modelling of the case studies has been developed through Revit families, both internal (in place elements) and external. A family is a group of elements with a common set of properties, called parameters, and a related graphical representation (Autodesk, 2018). There are multiple categories of families: generic models, doors, windows, foundations, mechanic models, etc. Different elements belonging to a family may have different values for some or all of their parameters, but the set of parameters (their names and meanings) is the same. These variations within the family are called family types or types.

There are three types of families:

- System families contain family types that are used to create basic building elements such as walls, floors, ceilings, and stairs in building models.
- Unlike system families, loadable families are created in external RFA files and imported (loaded) in projects.
- In-place elements are custom elements that are created in the context of a project.

Loadable families can be parametrized to easily control and change the family type without accessing the family file, just changing parameter values in the central model. Loadable families are created in HBIM to model repetitive elements in the project or in similar projects, each means, which can be reused in the future. This families can be shared in blogs or family's websites so other BIM modellers can used them.

A previous modelling in the project file is always necessary to host families. In HBIM projects modelling need to be adapted to the time degradation of the hosting structures. The protocol, layer C, to model parametrised HBIM families is:

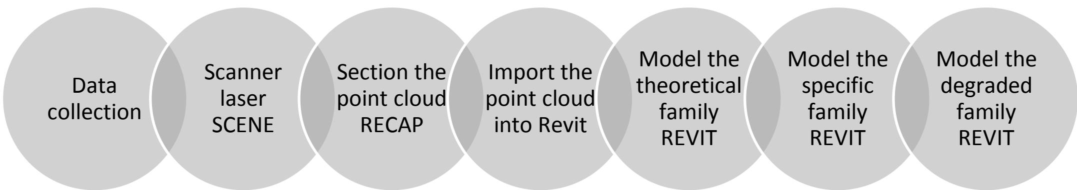


Figure 96. BIMlegacy protocol-3, layer C, guide to perform the general modelling, 2017.

1. Freehand data collection. HBIM families usually represent small portions of a building but with a great level of detail. Therefore, it is necessary to perform an initial visual inspection and the first sketches to understand the constructive element.
2. Scanner data collection. High-resolution scanning needs to be performed in the constructive elements to capture as more detail as possible. It is recommended to perform the scanning including photography scanning to provide colour to the point cloud. This will help to document the pathologies. The union and cleaning of the point cloud entail the same process that a generic data collection with scanner laser.

3. Sectioning the point cloud. The point cloud needs to be sectioned to better control the profiles and shapes of the constructive elements. For example, to model a cornice, it would be necessary to section the point cloud perpendicularly to show the shape and profile of the cornice.
4. Theoretical families. The motives, structures, and ornament of heritage buildings usually repeat from one to other building. Back in the days, there were not many manuals that the construction masters could use. They built by try and error repeating the successful items. On the middle age, the concept of originality did not exist, or at least not as nowadays; creativity connotation was different. Thus, in the historical buildings there are an important number of repetitive elements, which is perfect to use parametric families. In this step the repetitive elements, for example, a gothic arc, should be idealized and discomposed until creating a very simple element, but with all the characteristics.
5. Adaptation of the theoretic family to the specific case. The theoretic family should be adapted to the specific dimensions and characteristics of the constructive element that want to be represented. For example, the gothic arc theoretic family is modelled and the specific dimension of the arc the researchers want to represent is introduced. This represents the element just after its construction, so when it was in perfect preservation condition.
6. Family with the degradation of time. The perfect families need to be modelled with the degradation that they have (a.e. the scratches, the collapses, the colour degradations).
7. The families are inserted in different hosts in the architectonic HBIM model to complete it.

As example of how to follow this protocol, a gothic arc family is detailed below, Figure 97 (this figure was developed within San Juan project, in Valencia, so in Spanish language):

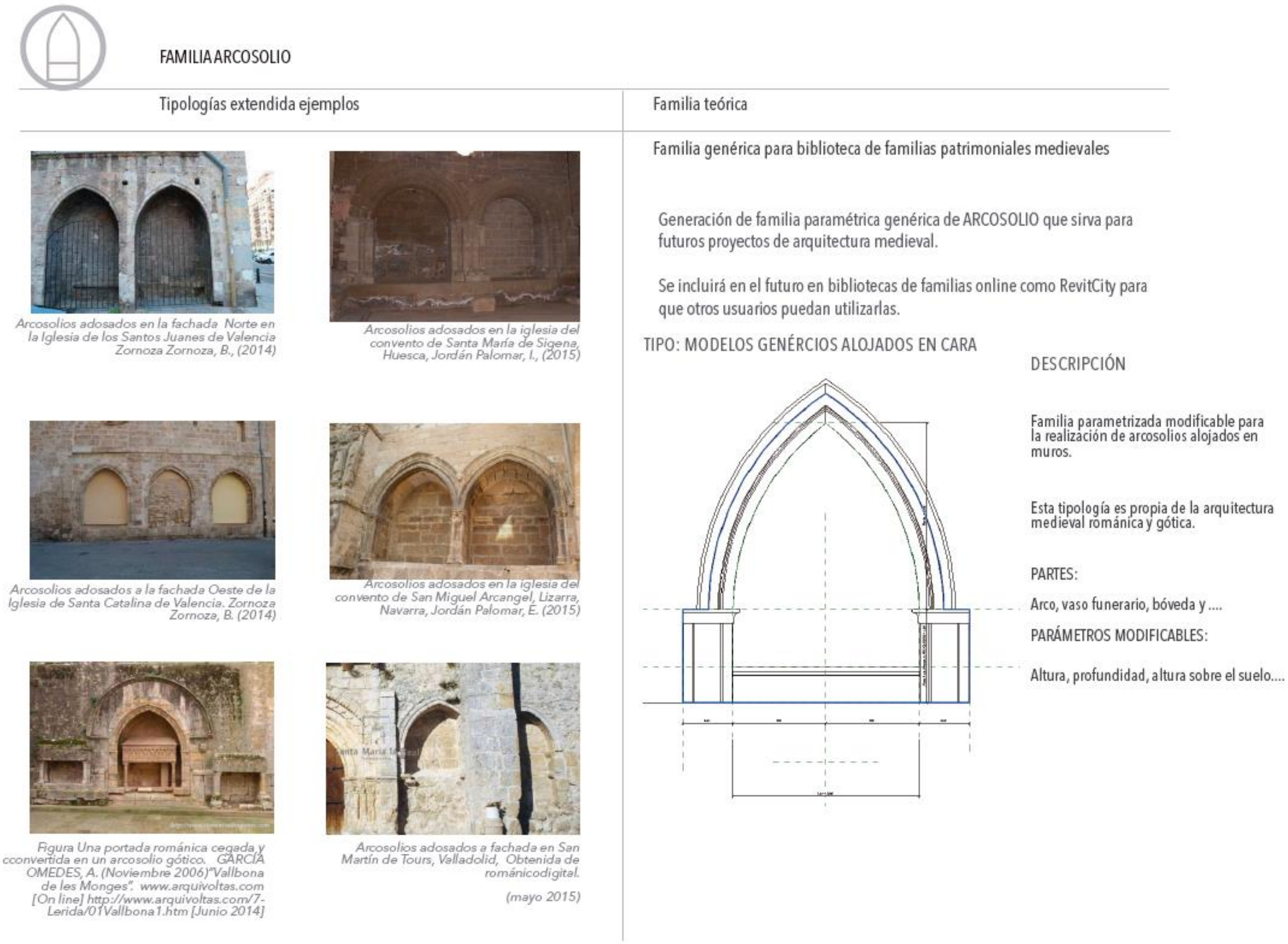


Figure 97. Example of specific modelling of a Revit Family of a gothic arc. Mr. Rubén March Oliver and Ms. Isabel Jordán Palomar, 2017.

Modelling sculptures and complex shapes

Heritage buildings usually have sculptures and complex shapes that need to be documented in the HBIM model. However, there are not specific tools in the BIM software to achieve such a complex task. The modelling of a sculpture with BIM software like Revit is not accurate and takes a lot of time, which is not productive (García Valldecabres *et al.*, 2016). Mr. Jose Charco did his master's final project researching in this topic in relation with the Instituto de Restauración del Patrimonio with Ms. Elena Salvador, Prof. Jorge García Valldecabres and the author of this thesis. There are different types of modelling starting of a point cloud that were experimented within San Juan project to understand the benefits and issues of each one.

Figure 98. Example of heritage sculpture, 2017.

- Mesh models: the points are joined with lines creating a triangle mesh. The meshing process transforms large point clouds quickly and easily to obtain light-weight, accurate and aesthetic models. There are different meshing strategies to give the best result depending on the quality of the original point cloud. The process to obtain mesh models is:
    - In a first step, create a very rough mesh in order to have quickly the global shape.
    - In a second step, refine this rough mesh with the point cloud by adding triangles where there were details.

With the mesh models very accurate shapes are produced and with great definition, but nets are just superficial sheets and do not define the inside construction system (see Figure 99). However, nets are very useful when defining sculptures in heritage buildings since heritage stakeholders usually demand extremely accurate models (Megahed, 2015).

Figure 99. Example of a mesh model of a sculpture, 2017.

- Geometrical model: it is a BIM model with geometrical shapes and parametrised elements. As Sennett and Gibson (2013) said a geometrical model is technology crafts. It is a three-dimensional parametric intelligent model with an underlying database linked with each geometrical element. Geometrical models built not just the outside but also the inside (Sennett and Gibson, 2013). Figure 100 represents some sculptures of San Juan HBIM model generated with the simple tools of Revit that the author of this thesis generated within san San Juan case study. These pieces are humanoids shapes and animals representations which were created as an external family in Revit.

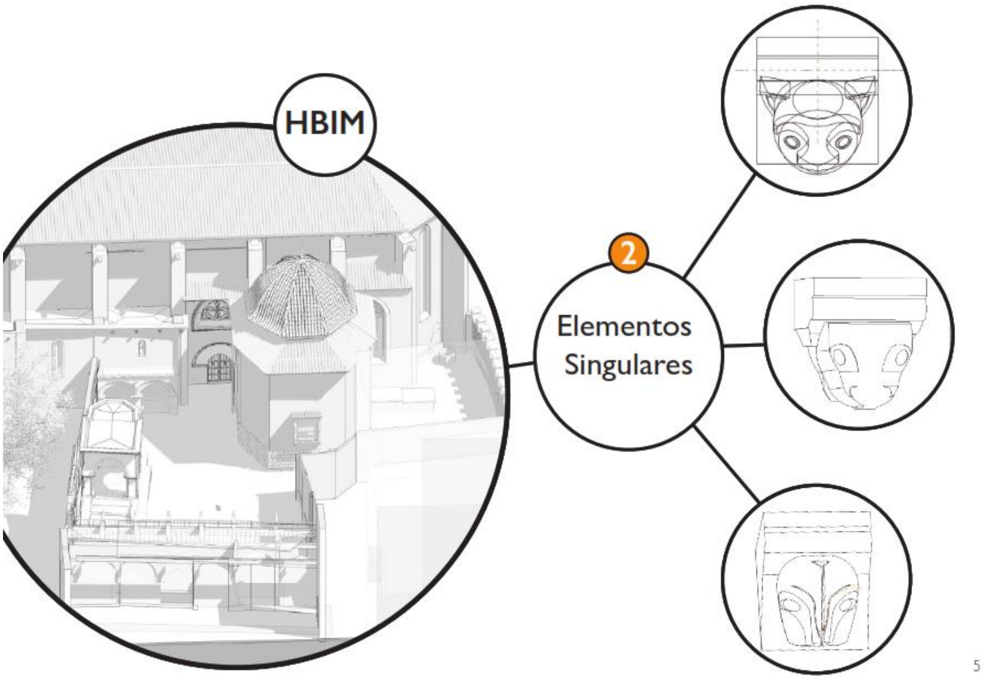


Figure 100. Sculptures of San Juan that were modelled with geometrical tools in Revit. Charco presentation with images of Ms. Isabel Jordán Palomar, 2017.

Literature research was performed, and few sculptures of San Juan were studied and modelled in different ways in order to design a method to insert the sculptures in a BIM software easily and with good graphic quality. As a result, this guide to model sculptures in Revit was created, Figure 101, and also a proposal of software to use in each of the steps of the protocol such as the programs of the Autodesk Company (Figure 102).

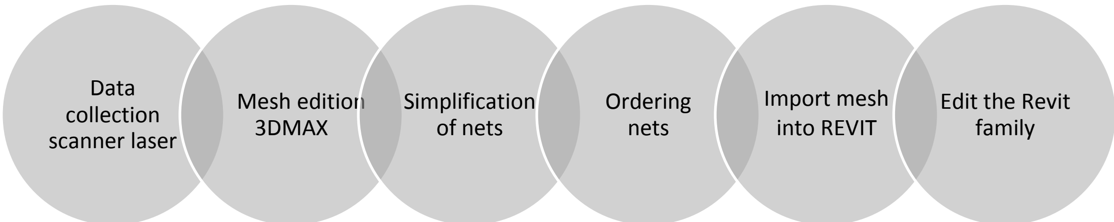


Figure 101. Protocol to model sculptures and complex shapes with a BIM software, 2017.

Figure 102. Proposal of software to use in each of the steps of the protocol to model sculptures in HBIM. Charco, 2017.

This protocol was implemented in a case study of San Juan, the Virgen del Milagro sculpture, that is situated inside a chapel in the south courtyard. The results of each of the steps are detailed bellow.

1. Data collection with scanner laser

To perform a high-quality data collection, it was necessary to do a scanning plan (see Figure 103). The point clouds obtained in the data collection with the scanner laser were joined and a unique point cloud was obtained.

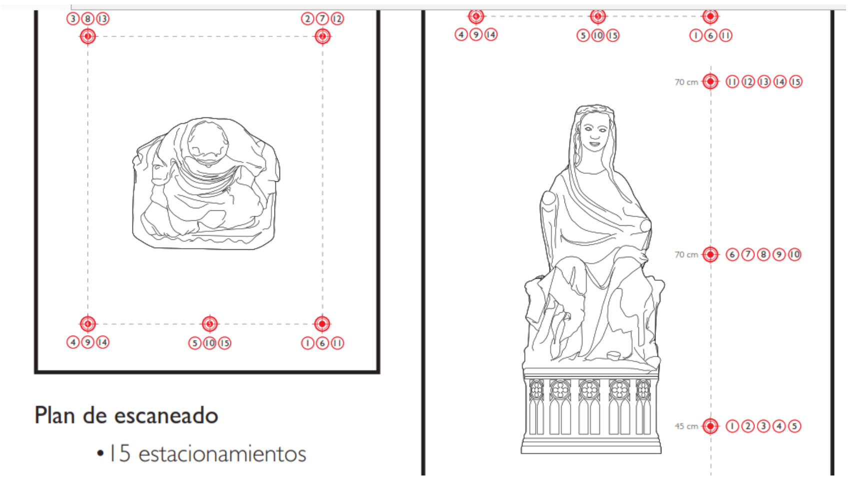


Figure 103. Scanning plan of the sculpture of the Virgen del Milagro. Charco, 2017.

2. Mesh edition 3DMAX

The point cloud obtained had millions of points that were joined to create a mesh. However, this mesh is not very useful without ordering and simplification (see Figure 105). Point clouds can be converted into nets using different software, Figure 104 is the result of convert all South Courtyard into a mesh file using 3D Reshaper software. The conversion of the Virgen del Milagro point cloud into a mesh was performed using Instant mesh software because Instant mesh is easier to use.

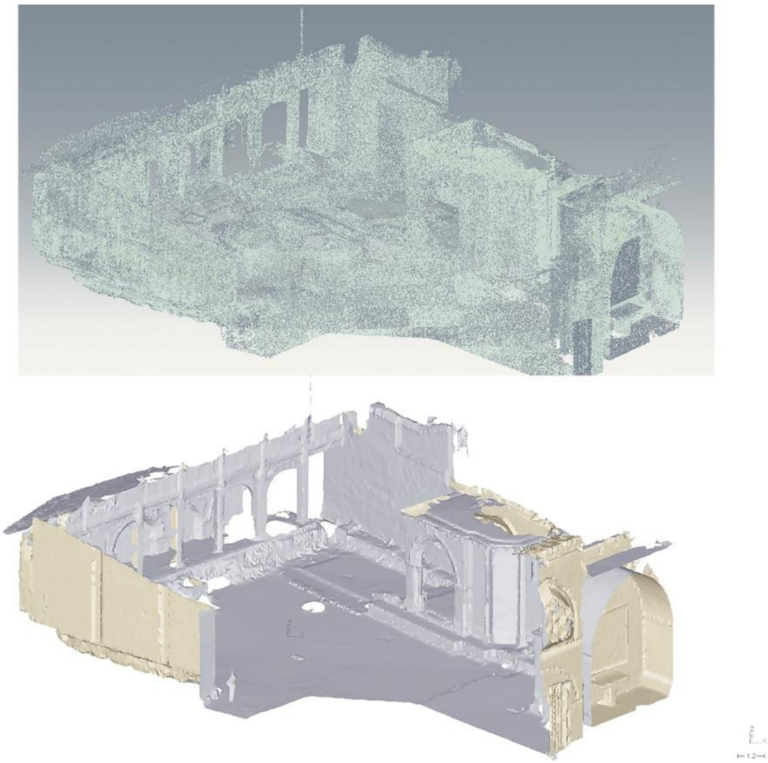


Figure 104. Mesh generation from a point cloud with the software 3D Reshaper, 2017.

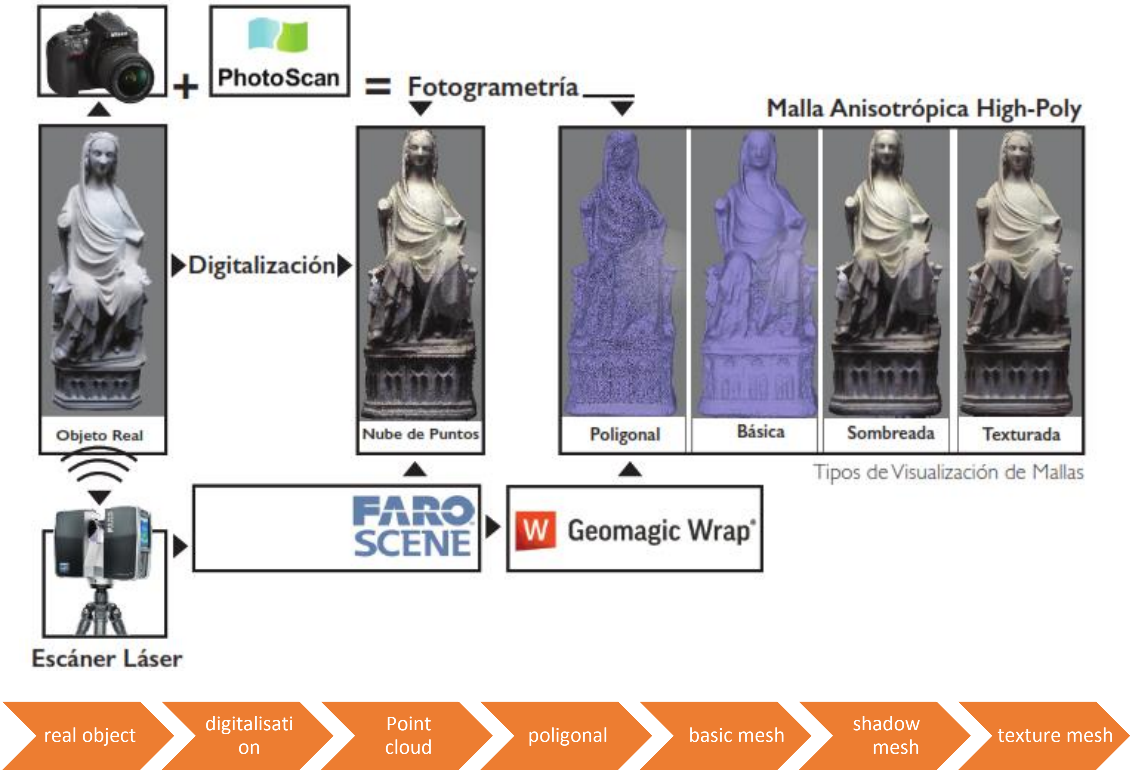


Figure 105. Steps to transform a point cloud into a mesh. Charco, 2017. The image was originally developed in Spanish so the translation of the main steps into English was made by Jordán, I., 2017.

3. Simplification of nets

The mesh was simplified with Geomagic Wrap software after a retropology process, Figure 106.

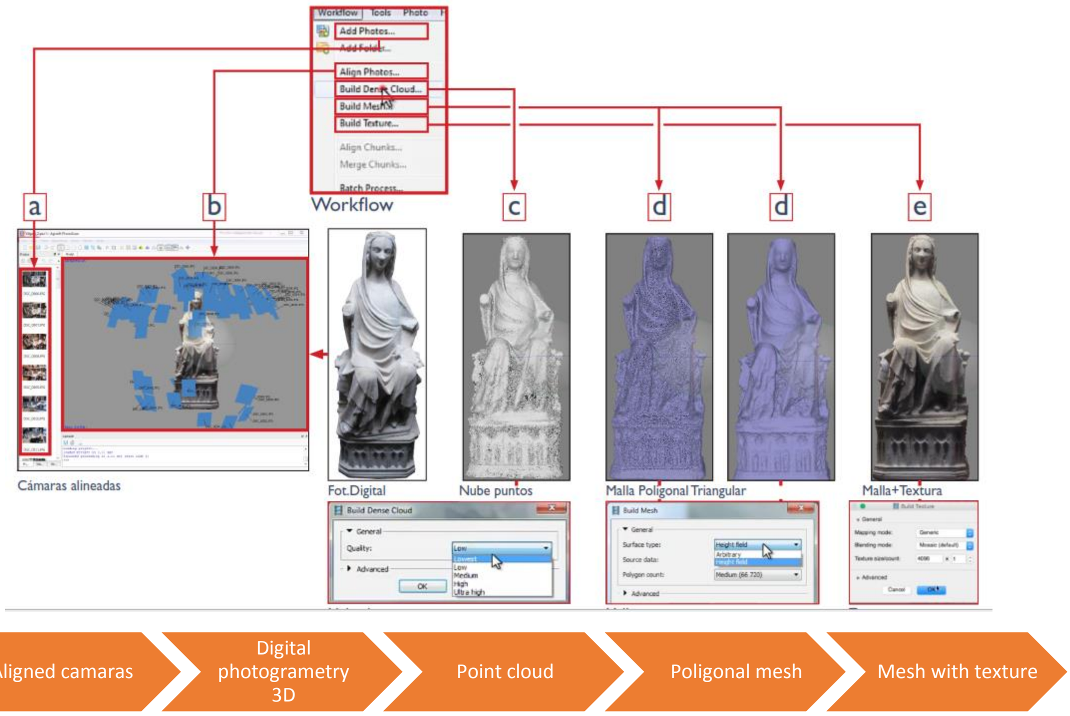


Figure 106. Simplification of nets process. Charco, 2017. The image was originally developed in Spanish so the translation of the main steps into English was made by Jordán, I., 2017.

4. Ordering nets

   The anisotropic or disordered mesh was converted into an ordered or isotropic mesh, Figure 107. This process helps to reduce the size of the file.

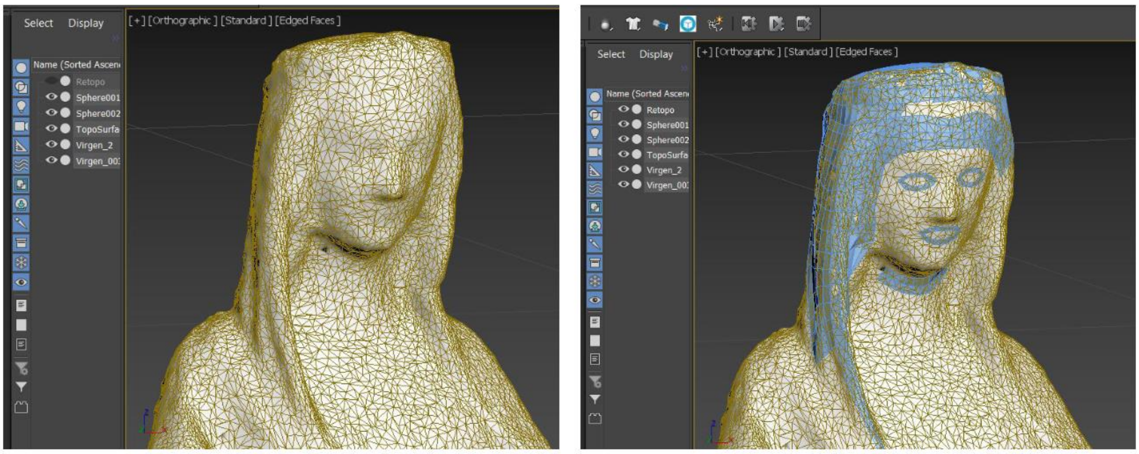


Figure 107. Ordering the Virgen del Milagro mesh. Charco, 2017.

5. Import the mesh into REVIT

   The mesh needed to be exported from Meshlab free software into a Revit file, Figure 108. Few attempts were required to find the configuration that generates a high quality mesh.

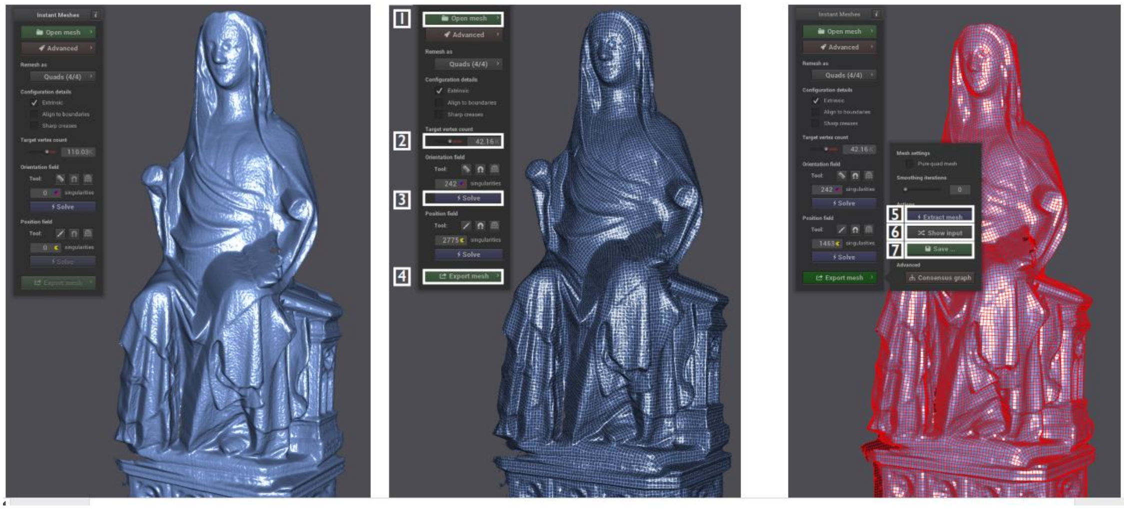


Figure 108. Exportation of the Virgen del Milagro mesh into Revit. Charco, 2017.

6. Edit the Revit family

   The isotropic mesh was inserted into the Revit project as a family within the “generic models” category that is the most flexible. This family was parametrised with visibility and materials parameters (see Figure 109 and Figure 110) and was inserted into San Juan model to check how the sculpture family fitted with the rest of the HBIM model.

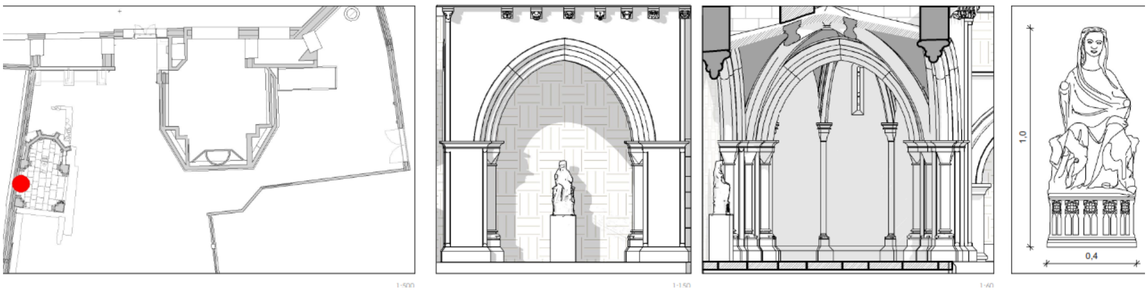
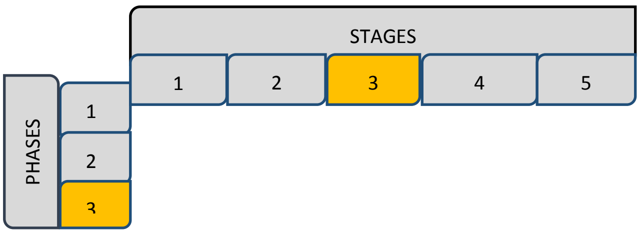


Figure 109. The Virgen del Milagro Revit family inserted in San Juan project. Charco, 2017.

Figure 110. Render of the Virgen del Milagro Revit family inserted in San Juan project. Charco, 2017.

4.3.3 CHANGES PERFORMED IN BIMLEGACY PLATFORM



The focus group was recorded, transcribed, and analysed with the scientific tool N-vivo, (10 Annex 3. Qualitative data analysis using Nvivo) and a list of changes was listed to improve BIMlegacy platform. The platform was completed considering the stakeholders' documental needs and the difficulties of HBIM modelling (a.e. needed to improve the definition of the archaeologist' modelling tasks and the representation of heritage buildings pathologies). The following improvements were performed:

- A new role for the archivist was created in BIMlegacy platform.

- The archaeologist' modelling tasks were defined as well as the archaeology fields in the BIMlegacy platform.
- A digital agenda in the BIMlegacy platform was added to manage the logistics, visits, and meetings in the monument.
- BIMlegacy platform was updated with a new image and graphic tool to fulfil the considerations made by some focus group participants (see Figure 111).

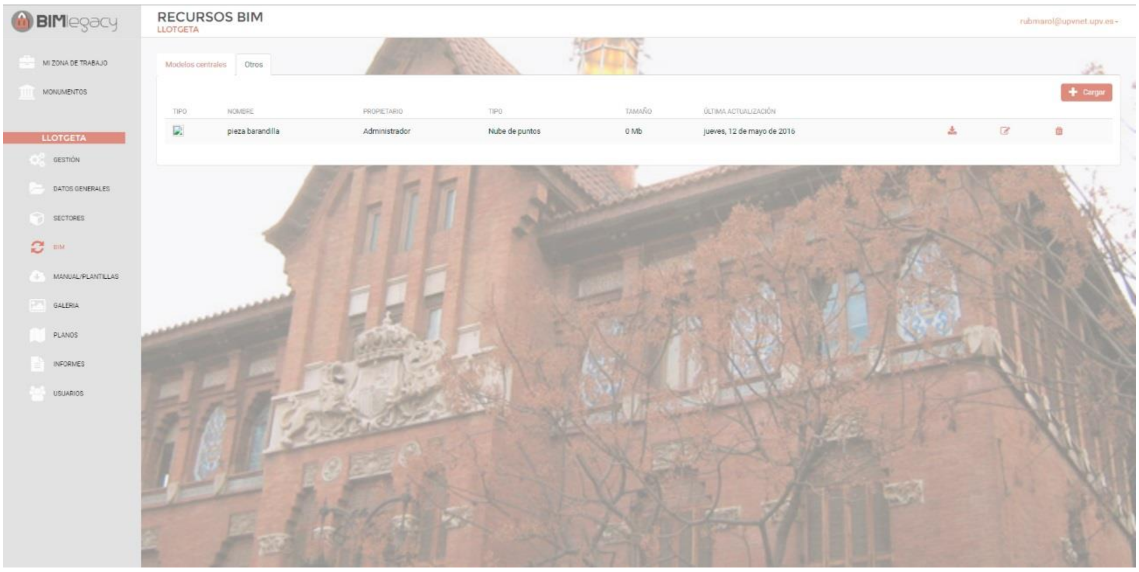


Figure 111. New images and graphics browser generated in BIMlegacy platform, 2017.

- Some tools were simplified to improve the functioning of the platform so non-technical stakeholders could work better.
- More functioning test were performed and the workflow of the Revit plug in was improved, Figure 112.

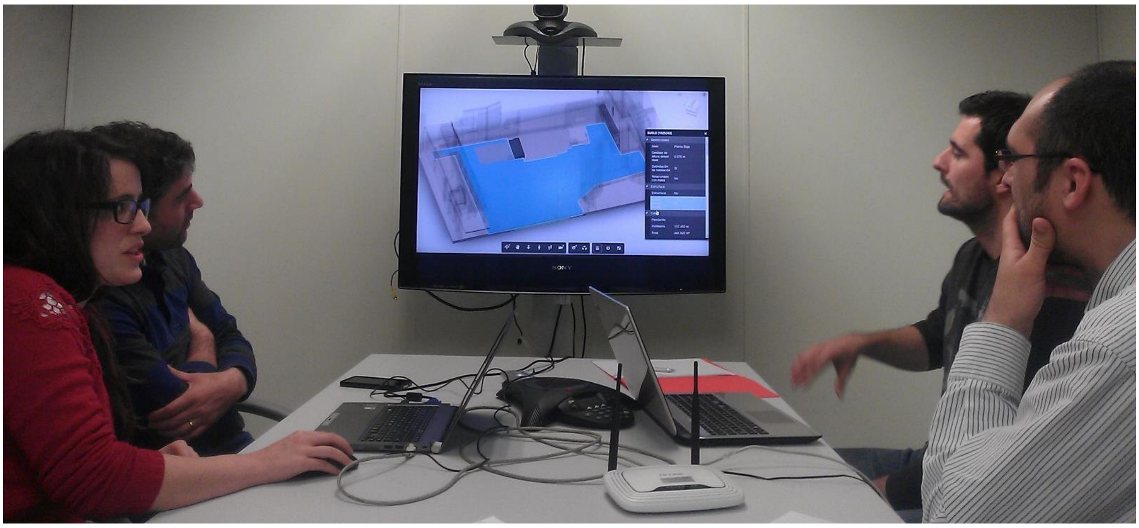


Figure 112. Functioning test performed with the IT team, 2017.

- A new option was designed to control models with subprojects, Figure 113.

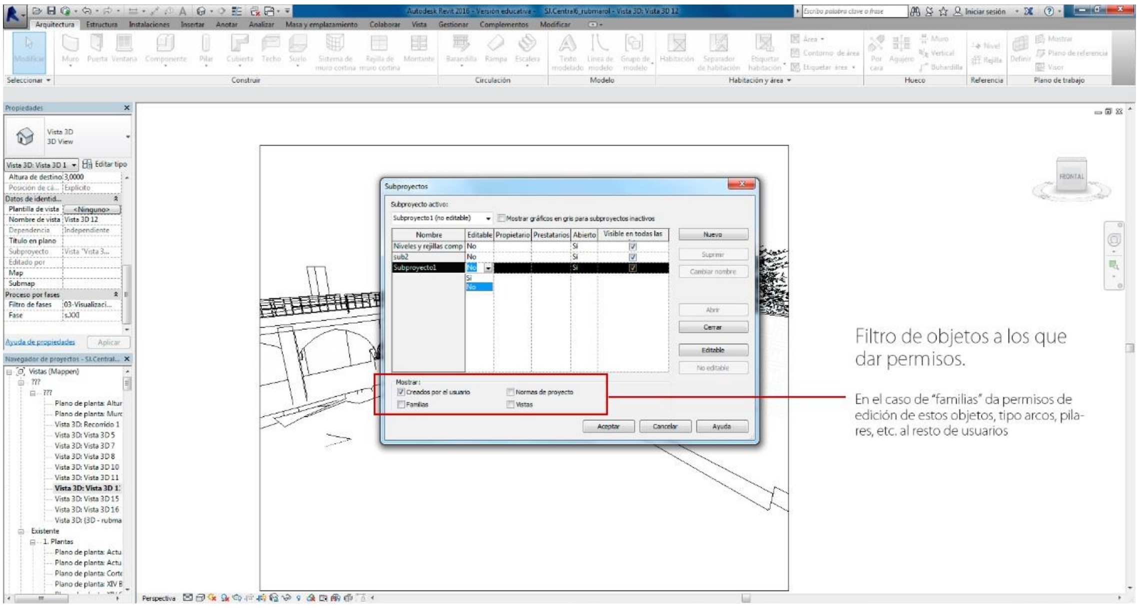


Figure 113. Testing BIMlegacy plug in for Revit, 2018.

- Two menus were added to document pathologies and systems degradation in the platform.

Figure 114. BIMlegacy platform with new menus to insert pathologies, 2018.

4.4 DISCUSSION

This chapter presents a protocol and platform named BIMlegacy- 3 aiming to help heritage stakeholders involved in medium size building interventions. It focuses on buildings owned by private institutions. It has been demonstrated that BIMlegacy protocol and platform improves the workflow in the heritage teams however, an extended discussion is revealed bellow to compare and contrast the doctoral thesis results with the scientific literature findings.

4.4.1 BIMLEGACY PROTOCOL BENEFITS

The interviewed stakeholders manifested that BIMlegacy is a successful protocol and HBIM is the future of heritage architecture management. They also considered that BIMlegacy steps were correct and that the protocol was easy to understand. The list of valuations extracted from the interviews, workshop and focus group analysis is explained bellow:

4.4.1.1 Non-technical stakeholders in BIMlegacy protocol

The literature further states the need to include traditional heritage stakeholders and processes as part of the BIM workflow (Afsari *et al.*, 2016). BIMlegacy includes traditional heritage workflows and synchronises stakeholder's activities with the HBIM models through the proposed online platform, supporting their active participation in the intervention. This was also highlighted as a benefit of BIMLegacy by the research interviewees (quotes from interviews in case study 2).

Heritage researchers like Megahed highlighted the need of including non-technical professionals within BIM system (Megahed, 2015). BIMlegacy's simplicity, which was specifically designed to make it easier to understand by non-technical stakeholders, can aid decision making. The visual online platform of BIMlegacy fosters collaboration between stakeholders in real time generating the creative conversation that is needed and allowing consultants to see each other's work; e.g. the legal documents, the construction reports according to the workshop discussion. This was one of the conclusions of the workshop with the interdisciplinary stakeholders (transcription of Huddersfield workshop with interdisciplinary stakeholders).

BIMlegacy promotes a high implication and supervision of the **monument owners** in the project and the construction works since there are iconic monuments.

4.4.1.2 Unification of information

The unification of information in the HBIM models and clash detection has the potential to reduce rework and consequently the heritage intervention's costs (Baik, 2017), due to a reduction of errors which generally happen because of data dispersion (Volk *et al.*, 2014). Although the implementation of BIMlegacy may be costly initially, the project development times should reduce over time. The work processes' standardisation proposed in BIMlegacy supports the organisation of data and processes by heritage teams, which should provide economic benefits in the long term (transcription of Huddersfield workshop with interdisciplinary stakeholders).

4.4.1.3 Documentation in BIMlegacy protocol

One of the main advantages highlighted in the literature for the use of HBIM is its ability to gather buildings' documentation centrally (Fai *et al.*, 2011). However, this may lead to overloading the HBIM models with useless information and missing some of the stakeholder's data, according to the analysis of the interviews. BIMlegacy contemplates the holistic documentation of heritage interventions within the online platform linked with 3D models, which will be specifically designed for different purposes (e.g. a maintenance model, a historic documentation model). Furthermore, permission controls within the plug-in and online platform facilitates the non-duplication of information (quotes from research interviews in case study 1).

4.4.1.4 CDE in BIMlegacy protocol

Past HBIM studies discussed the potential of common data environments and recommended their further study for heritage architecture (Antonopoulou and Bryan, 2017). (Dore and Murphy, 2017). (Littlefield, 2017). (Marzouk and Hawas, 2017). The research participants recognised BIMlegacy's innovative online platform as key factor for the success of the protocol (research interviews in case study 2).

4.4.1.5 Preservative maintenance in BIMlegacy protocol

Preservative maintenance information linked with the HBIM model improves the quality and accuracy of the operational systems in the building (Megahed, 2015). In this research, the focus group results demonstrate that maintenance models should be as simple as possible, containing only the necessary information for maintenance activities (focus group with interdisciplinary stakeholders).

4.4.1.6 Modelling guidance

Heritage architectonic representation requires a high level of detail in order to satisfy the cultural documentation and drawing principles (Green and Dixon, 2016) (Edwards, 2017). The automatic updating of drawing views together with the creation of HBIM families and libraries undoubtedly helps the heritage project's quality (Antonopoulou and Bryan, 2017). According to this research (quotes from research interviews in case study 1 and 2), achieving a quality HBIM model is very time consuming. BIMLegacy includes modelling recommendations to accelerate HBIM modelling and it establishes clear LOD for each step. Detailed modelling provides to the modeller a great knowledge of the building (López *et al.*, 2017). For example, when modelling a gothic vault, the modeller is forced to learn its metric rules. Standardisation and heritage BIM libraries were not considered as relevant for the protocol success as previous literature indicates that in heritage architecture diverse elements will have their own particularities, and so there are limitations in the potential of using standardised libraries of objects (Construction Industry Council-CIC, 2013).

4.4.1.7 Historical phases in BIMlegacy protocol

In accordance with Brumana the representation of all historic phases of a building in one single file allows the understanding of the building evolution, but the LOD levels in HBIM were not defined yet, which makes it difficult to get the right representation of historical phases (Brumana *et al.*, 2013). BIMlegacy establishes LOD depending on the quantity of information of each constructive hypothesis –usually historic phases are difficult to model due to the lack of knowledge about the past appearance of the building–. The representation of ancient historical phases is fundamental to document the heritage building. In addition, historic phases have a great potential for the monument's cultural dissemination according to the research results (transcription of the focus group with interdisciplinary stakeholders).

4.4.1.8 4D and 5D within BIMlegacy protocol

4D and 5D HBIM simulations have the potential to reduce conflicts and changes during construction and improve the construction budget's accuracy, the constructability of the designed techniques, and the standard of the building's energy consumption (Dore and Murphy, 2017). The designed protocol contributes to this by specifying modelling guidelines, including the LOD simulation's and the requirements of the "as built" heritage models (transcription of the Huddersfield workshop with interdisciplinary stakeholders).

4.4.2 BIMLEGACY PROTOCOL ISSUES

4.4.2.1 Model property and maintenance

The protocol does not specify who must create and maintain the HBIM models, which is unclear according to various guides, protocols, and scientific articles. (Antonopoulou and Bryan, 2017). According to the focus group participants (transcription of the focus group with interdisciplinary stakeholders), two different protocols are required depending on the type procurement process; it can be integrated project delivery or traditional approach with different agents. However, different researchers have different point of views. According to traditional basis of Lean construction, the integrated project delivery performs better results in projects.

The BIM philosophy rules the communication between all agents. However, some focus group participants highlighted that the owners must communicate exclusively with the project management, and not with the contractor. The literature, in contrast, recommend an open communication between contractor, client and designers to improve decision making (Du *et al.*, 2018).

Implementing HBIM requires an important economic investment, which is the main concern for the owners. The protocol does not study the acquisition of hardware and informatics even though it is fundamental to the real application of BIMlegacy.

4.4.2.2 Governments slow HBIM adoption

Different countries are adapting their construction legislative frames to BIM systems, but it seems that they are having problems to achieve this aim (Gurevich *et al.*, 2017). Heritage constructions have extra legislative regulations to protect their cultural values and historic background. In the United Kingdom, the adoption of BIM by part of these bodies was supposed to be completed by now, according to the Government's Construction Strategy (Bolpagni, 2013). However, the International BIM Report 2016 (Royal Institute of British Architects - RIBA., 2016) shows that even though a positive attitude exists towards the fact that the Government is taking the lead on BIM, local and national institutions are not yet prepared for such a change.

More qualified technicians and more resources are required to apply BIM effectively in the public administration. This aligns with findings of other scientific papers (Cabinet Office: Annual Reports and Accounts 2012-13, 2013).

Heritage inspectors and governmental architects need to learn BIM according to the literature (Royal Institute of British Architects - RIBA., 2016). However, after the results of the case studies (quotes from research interviews in case study 1), it can be stated that **heritage inspectors** do not need to work with the HBIM model; they just need a visor as is indicated in the protocol.

4.4.3 BIMLEGACY PLATFORM BENEFITS

According to the literature review, the use of BIM platforms assisted the increment of productivity of the projects since all the stakeholders' information is synchronised (Lee *et al.*, 2017). The use of BIMlegacy in San Juan project allowed the synchronisation of the information in real time, which accelerated the response time of the involved stakeholders.

The results of San Juan project, carried out with BIMlegacy, proves that it allows the complete heritage documentation and it improves the workflow between divergent stakeholders and produces a higher quality project (quotes from research interviews in case study 2). San Juan project was developed with higher quality than other recent projects due to the adoption of BIMlegacy as a work platform. During the first two months San Juan project' tasks that were developed with BIMlegacy took more time than in previous projects not developed with the platform. However, once the stakeholders were familiarised with HBIM methodology the productivity increased considerably.

4.4.3.1 Divergent stakeholders working together

Heritage projects involve divergent stakeholders who traditionally work independently producing economic losses. HBIM has not totally solved these inefficiencies as some of these stakeholders could not participate within the HBIM process (Dainty *et al.*, 2017; Gurevich *et al.*, 2017). BIM platforms emerged to unify and synchronise all stakeholders' information. The level of collaboration between different stakeholders was higher in this last project carried out with BIMlegacy than in previous projects in San Juan. The previous projects carried a small number of mistakes as for example, the inaccuracy between the architecture survey and the archaeological survey. With BIMlegacy, the historian and the archaeologist worked actively together and checked the coherence of the architectonic and archaeological model. Also the owner could participate within the project, as different guides and protocols suggest (Royal

Institute of British Architects - RIBA., 2016). The manager of San Juan reviewed the project evolution and the 3D models helped him to understand and visualise how the building would look after the construction works (quotes from research interviews in case study 2). Everything was consciously approved by the property before the construction, which improved the project productivity as other investigations have also indicated

4.4.3.2 Heritage documentation improved

HBIM does not have into consideration historic and archaeological documentation (Dore and Murphy, 2017) only maintenance information is recorded (Forster and Kayan, 2009). BIMlegacy takes into consideration heritage documentation creating the website where the historian, art historian and documentarist could fully document the monuments. San Juan project was totally documented and the historic information, filled in BIMlegacy workspace, was synchronised with the architectonic information, added in the HBIM model (transcription of the focus group with interdisciplinary stakeholders).

4.4.3.3 Modelling issues improved

Modelling issues when modelling complex heritage structures were recorded in the scientific literature (Kassem *et al.*, 2014). Not all heritage stakeholders have the technical education to achieve historic modelling which excludes them from the heritage project tasks (Inyim *et al.*, 2014). In San Juan project the collaboration between historians, archaeologist, and architects was essential to build coherent evolution hypothesis. Those stakeholders discussed the possible evolution hypothesis through BIMlegacy and the architect then modelled the evolution following the archaeologist's sub-project with all the archaeologic remains. Thus, the historian was still involved in the process even though he did not model (quotes from research interviews in case study 2).

4.4.3.4 Construction budget

The literature review suggested that the budget estimations in heritage projects are very unstable. Controlling the construction budget is easier and more accurate when using BIM platforms since measurements are more precise (Lee *et al.*, 2017) and construction operations become more specific (Jeong *et al.*, 2016). The construction budget of San Juan was controlled with higher accuracy using BIMlegacy thanks to the real interaction between the contractor and the archaeologist, the restorer and the architect, which allows the contractor to attribute a realistic price to heritage budget activities. In previous projects, the communication between the contractor and the restorer or the archaeologist was indirect, but BIMlegacy allows them to communicate more effectively (quotes from research interviews in case study 2).

4.4.4 BIMLEGACY PLATFROM ISSUES

The last questions of the focus group invited the participants to focus the weak points and issues in the platform to improve it in the future. The list of possible improvements of BIMlegacy platform obtained after the analysis of the focus group (transcription of the focus group with interdisciplinary stakeholders).

4.4.4.1 Missing heritage stakeholders

There are important heritage disciplines that have not been included in BIMlegacy: paleo-pathology, ceramist artists, and palaeography. Other disciplines that were included, as the technical architect, needed to have more presence and acquire more relevance knowledge because they are essential to control and manage the construction works.

4.4.4.2 BIMlegacy documentation

A lot of time is required to enter the vast quantity of information archived in the monuments.

4.4.4.3 BIMlegacy interoperability

The HBIM models require a great interoperability to connect them with augmented reality systems and other maintenance software.

4.4.4.4 LOD in BIMlegacy

The level of detail of the HBIM model must be controllable because the model sometimes has to be simplified for the understanding of the monuments. The aim is that the cultural message could be rightly transmitted.

4.4.4.5 Poor BIM training

Heritage building stakeholders have in general limited BIM knowledge, and HBIM adoption is still low according to both research participants and recent literature studies (Dainty *et al.*, 2017). Thus, BIM legacy could be partially implemented, depending on the main goals of the heritage process, and this should in turn support its wider adoption.

Some stakeholders have been sceptical in the effectiveness of new technologies and HBIM, so detailed guidance for the implementation of BIMlegacy is needed. Training for non-technical stakeholders is need and further study is required to effectively teach these stakeholders.

4.4.4.6 Point cloud technology

Research participants agreed that the point cloud technology is an exceptional technique to document the existing condition of a building. However, laser scanning has limitations regarding what is inside the fabrics due to the limitation for recording the interior composition of the walls (Xiong *et al.*, 2013). Consequently, a building condition inspection to analyse the wall's cohesion and the structure's strength is still required. There will also be difficulties to access MandE information, which may not be existent or registrable with a laser scanner.

5 CONCLUSIONS

5.1 SUMMARY

Heritage **architecture projects present problems** related to the lack of clarity of processes, dispersion of information, disconnection of stakeholders, and the use of outdated tools. The literature review shows that HBIM need further research in terms of heritage management and not just architectonic survey; HBIM protocols and guides; its practical implementation; simplifying the laborious modelling task; need for better cultural documentation and dissemination; and need for a CDE to connect all the stakeholders' information. The existing HBIM protocols and guides present efforts to link conservation principles with BIM technologies. However, further research is needed in identifying specific stakeholder's needs, better aligning these with traditional heritage procedures, and evaluating these through practical implementations of HBIM (Antonopoulou and Bryan, 2017). There are not a specific HBIM platform which unifies in real time heritage information and serves as workspace for the interdisciplinary stakeholders.

The results of this research are a holistic **HBIM-protocol** and a **platform** to manage interventions in heritage buildings considering diverse stakeholders involved in historic architecture and contemplating the whole life cycle of the historic building. The research approach adopted to achieve the objectives was DSR and included three iterative phases and five stages to gain knowledge from the different evaluations.

As a result of the literature analysis, the two preliminary case studies, and the professional experience working with HBIM, a list of heritage stakeholders, a list of heritage buildings management needs, and a list of requirements to implement HBIM were developed. With these lists BIMlegacy protocol 1 was built. BIMlegacy **protocol was designed** to implement HBIM in heritage building's interventions, contemplating the whole life cycle of the building or asset. It integrates BIM with the specificities of heritage buildings: the diversity of stakeholders and processes present this type of buildings, the exhaustive documentation required, and the cultural values that need to be transmitted to the society. BIMlegacy **platform** synchronises the information of HBIM Revit models with BIMlegacy workspace information without latency solving the majority of issues pointed in the state of the art: lack of historic documentation and difficulties to synchronise the divergent stakeholders' information. The platform allows the **consultation and insertion** of information to those stakeholders who are not familiar with BIM software.

Two **case studies** in remarkable heritage buildings were developed, Fixby Hall in Huddersfield, England, and San Juan del Hospital of Valencia, Spain. Research techniques used include documentary analysis, semi-structured interviews, participative workshop, and two focus groups. BIMlegacy protocol and platform were applied to the case studies and its results were evaluated in a workshop and in a focus group with external participants.

5.2 ACHIEVEMENT OF GOALS

This section shows the comparison between the objectives, the contributions achieved, and the achievements of the goals of this investigation. All the information is presented in a table, Table 8, which is comprised of three columns. The first column contains the three objectives of the investigation. The second column presents the contributions both to knowledge and to practice revealed within this research that are discussed in section 4.4. Discussion .

In Table 8 each contribution has a letter in brackets at the end of the sentence that relates the contribution of this table with the next section 5.3 Contributions where these short sentences are further explained.

Table 8. Achievements of goals, 2019.

Objectives	Contributions (to Knowledge and to practice)	Achievements of goals
1. To understand the stakeholder's needs in heritage interventions and to study processes in heritage architecture projects.	Two preliminary case studies: • List of heritage stakeholders. (m) • List of heritage buildings management needs. (n)	4.1.1. Analysis of two preliminary case studies 4.1.2. List of heritage stakeholders 4.1.3. List of heritage buildings management needs
2. To identify the factual issues of HBIM application and the existing HBIM protocols and platforms.	HBIM state of the art findings (a): • The representation of the constructive-historic hypothesis is useful to develop architectonic projects. (s) • Heritage stakeholders have modelling difficulties. (b) • Non-technical stakeholders cannot fully participate within the HBIM process. (p) • HBIM projects do not take into consideration the historical and cultural legacy of the historic buildings. (n) • HBIM tend to focus on the architect and ignoring other stakeholders' requirements. (m) • HBIM implementation require higher economic costs than new construction architecture. (a), (j) • Educational protocols and guides to assist non-technical stakeholders are required. (j)	2.5.1. HBIM benefits 2.5.2. HBIM issues
	Existing HBIM protocols findings (j): • Do not specify the stakeholders who are involved in each step and their needs. (k), (m) • Need a better alignment between traditional procedures and BIM procedures. (n) Existing protocols require practical implementation of HBIM. (o)	2.6.1.2. HBIM protocol Drawbacks

	Existing HBIM Platforms findings (l): • There is not a specific platform where heritage stakeholders can unify in real time their information. (d) • Do not host the whole life cycle of the heritage buildings. (q) • Do not contemplate all stakeholders. (m) Do not synchronize the information in the HBIM models in real time. (d)	2.6.1.2.HBIM platforms Drawbacks
	HBIM personal experience List of requirements to implement HBIM in practice. A table with difficulties and solutions. (o)	0. List of requirements to implement HBIM 4.1.4.2. List of requirements to implement HBIM from the HBIM professional experience
3. To develop the solution		
3.1. Proposing a protocol (BIMlegacy) for managing the interventions in historical buildings with HBIM.	BIMlegacy protocol (j): • It was divided into eight chronological steps to cover all life cycle of heritage buildings. • It provides the ideal LOD for each step to guide heritage stakeholders. • It has three layers: ○ Layer A was designed to be clearly understandable by all people involved. ○ Layer B was designed to be understandable by both technical and non-technical stakeholders. (p) Layer C was designed to be used by technical stakeholders.	4.3.2. BIMlegacy protocol-3.
3.2. Designing a web platform prototype (BIMlegacy) that synchronises heritage information.	BIMlegacy platform (l): • It supposes a CDE for heritage architecture sector unifying heritage architecture information where: ○ Technical stakeholders work in Revit software with BIMlegacy plug-in. ○ Non-technical stakeholders work in BIMlegacy platform. General public access to quality information through BIMlegacy free-to access website.	4.2.3. BIMlegacy platform
3.3. Applying the protocol and the platform to two case studies.	Findings of the case studies: • BIMlegacy protocol and platform helped **non-technical** stakeholders to be active within the HBIM process. (p) • BIMlegacy protocol and platform unified the information and the **unification of the information** in the CDE reduced errors. It helped the distribution of information or the disconnection between the works of heritage stakeholders. (d) • Documentation in BIMlegacy improves the heritage documentation. It contemplates the holistic documentation of heritage interventions. (q) • BIMlegacy reduced the project time dedication and improved the	4.1.6.3. Fixby Hall findings 4.2.4.7. Conclusions and recommendations of San Juan case study.

	project quality. (j) • **Modelling guidance** reduced the time-consuming process of modelling. (j) • HBIM **constructive-historical phases** had a great potential for the monument's cultural dissemination. (s) • HBIM helps to determinate a correct intervention criterion. (c) BIMlegacy protocol and platform promoted the cultural diffusion of both case studies within local communities and society. (f)	
4. To evaluate BIMlegacy protocol and BIMlegacy platform with professionals through a workshop and a focus group.	Findings of the evaluations: • Protocols need to be simple and intuitive to be useful.(h), (k) • The non-designer stakeholders require specific training to understand the technology potential. (i) • The modelling issues improved using BIMlegacy. (b) • The **society** will **benefit** from BIMlegacy since the **rigorous information.** (r) • BIMlegacy protocol and platform promotes to make a complete **management** model for all the life cycle. HBIM maintenance models should be as simple as possible. (q) • HBIM models helped to study the wall stratigraphy due to the phases filtering. (g) • Filtering the information in BIMlegacy help stakeholders to form a decision. (e)	4.1.7. Workshop to evaluate BIMlegacy protocol-14.2.5. Focus group to evaluate BIMlegacy protocol and platform-2

All these contributions were analysed and divided into contributions to knowledge and contributions to practice depending on their own nature. Each contribution, numbered with the alphabetical letter in brackets, is further explained in the next section.

5.3 CONTRIBUTIONS

5.3.1 CONTRIBUTIONS TO KNOWLEDGE

(a) A compilation of the literature review of HBIM, existing HBIM protocols, and existing HBIM platforms findings was performed. This compilation is considered a contribution to knowledge because it will help other researchers to perform their literature review in HBIM faster. The most representative benefits and issues of HBIM are listed in sections 2.5.1 and 2.5.2. The most important benefits and issues of HBIM existing protocols are listed in sections 2.6.1.1 and 2.6.1.2. The best benefits and issues of HBIM existing platforms are explained in sections 2.7.1.1 and 2.7.1.2.

This research makes contributions to knowledge by highlighting issues and benefits in HBIM which were unknown before and needs in terms of implementing HBIM in practice. Such contributions were obtained from the analysis of the case studies, the workshop, and the focus group.

(b) HBIM literature highlights concerns about the practical effectiveness of HBIM in terms of modelling complexity (Migilinskas *et al.*, 2013) but it does not specify what are the most notable modelling issues. The analysis of the results of the case studies allowed the specification of the most notable **modelling difficulties** faced by heritage teams. These were modelling the wall stratigraphy, pathologies, and sculptures or complex shapes (a.e. cornices and scrollwork).

(c) Sophisticated monument registration and modelling helps in the understanding of the heritage building (Oreni *et al.*, 2014) and to determinate a correct **intervention criterion** according to the analysis of the case studies results. This supposes a benefit for HBIM professionals as they will be able to design heritage interventions with better intervention criterion.

(d) The use of **online platforms** is considered as an important benefit to assist HBIM implementation that was not stated before. In addition, rigorous information loaded by professionals and accessible to the public is highlighted as a benefit of HBIM.

(e) Simon (2006) states that the true problem of information systems resides in providing the correct filtered information to the people in coherence with the decisions they have to make, and not a lot of untreated information (Simon, 2006). The benefit of **filtering the information** in HBIM database systems according to the different stakeholders help them to form a decision is considered a contribution to knowledge because it was not highlighted in the literature before.

(f) The integration of the concept of cultural promotion and broadcasting of heritage through tourism as the national and international regulations stand is considered a potential HBIM benefit that was unknown before. HBIM should integrate the monument **preservation tradition** as international regulations, existing protocols and conservation recommendations have been considered in its design (Webb, 2003).

(g) The practice achieved in this investigation supports the potential of HBIM models to study the wall **stratigraphy** due to the phases filtering. Documenting the different phases results extremely important to perform quality stratigraphy studios with HBIM. Also, this study supports the benefit of HBIM to standarise the traditional constructive items.

(h) The analysis of the interviews with interdisciplinary stakeholders, the workshop and the focus group highlighted that protocols need to be **simple and intuitive** to be useful. Most existing protocols or guides are more complex and arguably harder to implement in practice. Clear graphics and simple vocabulary are useful tools to make complex concepts understandable (Inyim *et al.*, 2014). This is a need in terms of implementing HBIM in practice that was discovered in this research.

(i) Through this research it was found that the **non-designer stakeholders** require **specific training** to understand the technology potential; however, they should not be expected to use BIM software. Further research is required to study the specific needs of each non-designer stakeholder and to find an effective training to promote interdisciplinary collaboration. This specific research could not been addressed in this thesis and it will be exposed as future research, section 5.6.

5.3.2 CONTRIBUTIONS TO PRACTISE/ TECHNICAL AND MANAGERIAL IMPLICATIONS OR RECOMMENDATIONS

(j) BIMlegacy protocol itself is a contribution to practise as a process model to implement HBIM and an interesting practical trial of HBIM guidance. It is evident from the literature, **educational protocols and guides** to assist non-technical stakeholders were required (Holzer, 2016) as there are no other complete HBIM protocols to manage architecture heritage. BIMlegacy can improve the **quality** and performance of a heritage project.

(k) BIMlegacy easiness of use in practice is another contribution. The practical input resides in creating a **simple and user friendly HBIM protoco**l, developed based on previous literature as well as existing cases studies, which was demanded by different organisations (Maxwell, 2016; Architectural, Engineering and Construction (AEC) Initiative, 2015). It is **easy to understand** and use for all stakeholders and helps **non-technical** stakeholders to be active within the HBIM process without having to use complicated modelling software (a.e. heritage inspectors, monument owners, restorers, archivists, historians and art historians).

(l) The creation of a **platform** for the movable and immovable heritage's analysis, research, documentation, and management is innovative and represents a **huge improvement** in how the exchange of information occurs between the different professionals involved in heritage architecture. BIMlegacy platform represent a novel CDE for heritage, which **contributes** in exploring the best way to exchange information and improve heritage workflow. It proves it to be **noteworthy** in terms of problem-solving, this is because it helps the distribution of information or the disconnection between the work of architects, archaeologists, managers, and engineers, which was one of the main issues stated in HBIM literature (Arayici *et al.*, 2017).

(m) (n) (o) Previous research highlighted the need for considering **traditional heritage stakeholders and their processes** in BIM environments (Maxwell, 2016). As a result of the literature research and two exploratory case studies a complete **list of heritage stakeholders** (m), list of heritage buildings management needs (n), and a list of requirements to implement HBIM (o) in the BIMlegacy protocol was developed. This provides a contribution towards this need as it was designed based on the analysis of the traditional processes of real heritage work groups.

(p) BIMlegacy protocol helps **non-technical** stakeholders (a.e. heritage inspectors, monument owners, restorers, archivists, historian and art historians) to be active within the HBIM process without having to use complicated modelling software, which is considered a contribution to practice. With BIMlegacy building owners, archivists, monument managers and government agents can **easily provide inputs** to the process and participate actively in the project when using BIMlegacy improving the heritage workflow.

(q) The qualitative leap proposed in this research comes from the use of **HBIM** not only for the buildings' graphic survey (Brumana *et al.*, 2013) but to make a complete **management** protocol (Arayici *et al.*, 2017). Management involves the entire construction lifecycle which represents the most important advance because is the longest phase. The absence of scientific publications with HBIM's practical enforcement supported this point. Therefore, the generation of BIMlegacy protocol for analysis, research, dating, documentation, and architectural heritage management is a contribution to the management of heritage buildings and would be useful for worldwide architectural heritage.

(r) The **society** will **benefit** from BIMlegacy since the **rigorous information** uploaded by professionals and heritage experts will be accessible to the public. This brings the scientific founds to society which is one of the recommendations of the (European Commission, 2016). BIMlegacy respects the monument **preservation tradition** as international regulations, existing protocols and conservation recommendations have been considered in its design (Webb, 2003). Cultural diffusion with BIMlegacy contributes in long-term to assure heritage's protection. This is a benefit for **local people** interested in heritage and for the touristic sector**.**

(s) The representation of the **constructive-historic hypothesis** described in BIMlegacy protocol is useful, not just to develop architectonic projects as the literature indicates (Fai *et al.*, 2011), but also to promote the cultural diffusion of the monuments within local communities and society. Case study results prove that the HBIM models help to generate computer graphics for touristic diffusion and BIMlegacy website promoted heritage online.

5.4 APPLICABILITY OF BIMLEGACY PROTOCOL AND PLATFORM IN PRACTICE

Heritage groups that want to adopt HBIM methodology for the first time or heritage groups that already use HBIM but want to improve their workflow could apply BIMlegacy protocol and platform in practice. The type of projects that could benefit from BIMlegacy protocol and platform are medium size private heritage projects, however it could also be a frame guide in other types of projects such as larger public rehabilitations. BIMlegacy protocol could be the guide to achieve intervention projects in different phases of the life cycle. The technical stakeholders may be leading the application of the protocol as generally they have better BIM knowledge. The first action would be to identify the step of the life cycle and follow the correspondence sheet of the BIMlegacy protocol. Then the identification of the involved stakeholders would be required to allocate responsibilities of the different tasks described in the protocol. Ideally, there will be weekly, quinquennial or monthly meetings to discuss the progress reports and the achievements of the HBIM project. The clash detection of the different disciplines (a.e. archaeology, architecture, restoration) is important and it could be done after each step of the protocol. The evaluation of the quality of the HBIM models and the registration fields of BIMlegacy platform must be done at the end of the project and if something is updated in the heritage construction when the project is finished, it should be updated in BIMlegacy platform.

5.5 LIMITATIONS

1. The limitations of this research reside in testing BIMlegacy in more buildings to refine it further. BIMlegacy was applied partially on Fixby Hall and fully applied in San Juan del Hospital. However, BIMlegacy needs to be applied in other historic buildings to test its applicability to other project types with more stakeholders to improve it and measure benefits and issues. BIMlegacy would improve with new testing in new buildings. Ideally, the system would learn from each practical application.
2. The software solution, specifically the fact of host the software in an online platform, was very good option according to the external validation; however, it could be further improved it in terms of software functioning in various devices and the usability of the website. The software functioning and the usability of the website could be improved to be slightly more efficient. The user testing would definitively help to improve the software functioning.
3. BIMlegacy protocol does not specify who must create and maintain the HBIM models. Different researchers, governments and professionals shared different point of views in this matter. The analysis of the workshop focus group and the interviews with heritage stakeholders did not highlight a clear conclusion.
4. Implementing BIMlegacy protocol and platform requires an important economic investment, which is the main concern for the owners. The protocol did not study who must pay this investment in, for example, the acquisition of hardware and informatics even though it is fundamental to the real application of BIMlegacy.
5. The full adoption of BIMlegacy protocol requires the collaboration of government agents. The Government is taking the lead on BIM, local and national institutions are not yet prepared for such a change and HBIM adoption is being slowly. More qualified technicians and more resources are required to apply BIM effectively in the public administration.
6. Heritage building stakeholders have in general limited BIM knowledge, and HBIM adoption is still low according to both research participants and recent literature studies (Dainty *et al.*, 2017). Thus, BIM legacy protocol and platform could be partially implemented, depending on the main goals of the heritage process, and this should in turn support its wider adoption.
7. Layer C of the protocol could be further extended. The research needed to be limited to a doctoral thesis workload, however, the continuation of the development of Layer C is considered very helpful for heritage groups.
8. BIMlegacy did not totally solve the issues faced when modelling historic structures since the investigation focused on the information managing. The geometric modelling is time costly since it reproduces the original constructive process. HBIM modellers should have great software knowledge to be able to model historic buildings.
9. The level of detail of the HBIM model must be controllable because the model sometimes must be simplified for the understanding of the monuments. The aim is that the cultural message could be rightly transmitted. This was not investigated in this investigation because it was out of the thesis workload.

5.6 FUTURE RESEARCH

The optimisation of BIMlegacy protocol and platform would suppose a future research line. BIMlegacy requires testing it with other heritage buildings to improve both the protocol and the platform. This optimisation would involve the definition of who would create and maintain the HBIM models. BIMlegacy could highlight further ways to improve the unexplored area of tourism exploitation and BIM models. These ideas are linked with limitations 1 and 3.

The software functioning of BIMlegacy platform could suppose an interesting future research. It would require a complete testing of the platform in various heritage projects and with different stakeholders and hardware, which is linked with limitation 2.

Working with some of the technologies that BIMlegacy promotes requires **expensive software and hardware**. For example, point clouds or heavy HBIM models require specific expensive programs and powerful computers in terms of RAM, which is the memory or information storage in a computer that is used to store running programs and data for the programs (at least 16GB). This future research line is related with limitation 4.

Despite the efforts made in questioning the different stakeholders, the **legislative body's** needs require further research (Green and Dixon, 2016). The adoption of HBIM by Heritage Government Institutions may focus on the analysis of their human and material resources and their processes. This future research line is related with limitation 5.

Some heritage stakeholders are **sceptical** regarding new technologies, and this may negatively influence the implementation of BIMlegacy. Further research is required to study the specific needs of each non-designer stakeholder and to find an effective training to promote interdisciplinary collaboration. The HBIM **education** and awareness for non-technical stakeholders, such as building's owners and construction workers, and society needs further study following principles of usability and simplicity (Holzer, 2016). This future research line is related with limitation 6.

BIMlegacy protocol **layer C** can be extended in any step to further define more specific guidance. According to BIM preservative maintenance in recent studies (Ilter and Ergen, 2015), the "use" phase is the most important. The "use" phase of the protocol, step 7 and 8 of BIMlegacy protocol, has not been developed in layer C, which means that specific protocols to manage preservative maintenance, heritage education and cultural dissemination could be developed in the future. Also, the rent controlling and the furniture inventory through online platforms could be an interesting line of research. For example, the ongoing doctoral thesis of Mr. Elena Salvador García develops the use stage of the protocol specifically step 8 (Heritage education and cultural dissemination). This future research line is related with limitation 7.

Interventions on historic buildings are usually **small-scale projects** developed by small construction firms. Hence, a future research line could be used to understand how to implement BIMlegacy in such small firms. This idea is related with limitation 1.

The initial geometric modelling is time consuming since it reproduces the original constructive process and all the parameters need to be defined. A possible line of future research can address the modelling issues that were not resolved in this investigation, which is linked with limitation 8 and 9. Layer C of the protocol “Modelling sculptures and complex shapes” could be studied further. The pathologies and the **degradation’s** representation is an important concern amongst the HBIM community since its modelling is exceedingly laborious (Arayici *et al.*, 2017). To use BIMlegacy correctly requires a detailed HBIM modelling in terms of pathologies and degradation. Innovative ways to represent **sculptural**, degraded or artistic elements with HBIM needs to be researched further (Dore and Murphy, 2017).

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8 ANNEX 1: RESEARCH LEARNING

This annexe was developed to provide foundation of knowledge on the research topic. The Ph. D. candidate needed to understand the research philosophy basis and the research strategies to develop their own research design. This annexe is a synthesis of the learning process and a synthesis of research philosophy and research techniques as basis of this doctoral thesis.

8.1 RESEARCH PHILOSHOPY

Research philosophy is the all-encompassing term used to communicate the development of knowledge and the nature of that knowledge in relation to research (Saunders and Lewis, 2012). Grix (2010) states that ontology and epistemology are the foundations upon which the research is built (Grix, 2010).

Construction management research and social research are supported by ontology and epistemology philosophical disciplines (Walliman, 2017; Crotty, 1998). The philosophical basis of design science takes into consideration four branches in the research philosophy (Saunders *et al.*, 2009):

- Ontology describes the nature of the reality.
- Epistemology explores the nature of knowledge.
- Methodology is the development; it measures the impact of the created artefacts in the designed system.
- Axiology is the study of values.

Table 2.3 Philosophical Assumptions of Three Research Perspectives

Research Perspective			
Basic Belief	*Positivist*	*Interpretive*	*Design*
Ontology	A single reality Knowable, probabilistic	Multiple realities, socially constructed	Multiple, contextually situated alternative world-states Socio-technologically enabled
Epistemology	Objective; dispassionate Detached observer of truth	Subjective (i.e., values and knowledge emerge from the researcher-participant interaction)	Knowing through making: objectively constrained construction within a context Iterative circumscription reveals meaning
Methodology	Observation; quantitative, statistical	Participation; qualitative. Hermeneutical, dialectical	Developmental Measure artifactual impacts on the composite system
Axiology: what is of value	Truth: universal and beautiful; prediction	Understanding: situated and description	Control; creation; progress (i.e., improvement); understanding

Figure 115. Table of the Philosophical assumptions according to Saunders (2009).

This philosophical basis is explained in further detail in the following sub-sections.

8.1.1 ONTOLOGY

Ontology addresses the nature of reality and its characteristics explaining assumptions about reality and knowledge (Dainty, 2008). It is divided into two branches, objectivism and subjectivism, which some authors consider also constructionism (Bryman, 2008).

Objectivism takes into consideration social phenomena as the independent realities of social actions. It purports “the position that social entities exist in reality to, and independent from, social actors" ((Saunders and Lewis, 2012)p 131). This viewpoint lends itself to the scientific method of enquiry in that the elements that can be subjected to a quantitative analysis are investigated. Therefore, by its nature, the scientific method is reductionist (Creswell *et al.*, 2007). Some authors also name it relativism, which believes that reality is transmitted by society depending on culture or language, and ontology positions (Fitzgerald and Howcroft, 1998).

Subjectivism considers that it is the perceptions and actions of the social actors that create the social entity itself and that the continuous interaction of the social actors results in the constant state of change in the social phenomena (Bryman, 2008). Social constructionism views this reality to be socially constructed and helps with the understanding of the details of what is happening because of this interaction. Some authors also name it **constructivism** ontology and define it as the discipline that supports that social phenomena and their meanings are created as the product of social interaction which changes with time (Bryman and Bell, 2007).

8.1.2 EPISTEMOLOGY

Epistemology is concerned with the theory of knowledge regarding its methods, validity, scope, and the distinction between justified belief and opinion. It investigates the origin, nature, methods, and limits of human knowledge. Saunders and Lewis (2012), identify three aspects of epistemology: positivism, realism and interpretivist (Saunders and Lewis, 2012).

Positivism focus on the social phenomena (Walliman, 2006) recognising just the non-metaphysical facts and phenomena (Walliman, 2017; Fellows and Liu, 2015). It believes that only "factual" knowledge gained through observation, including measurement, is reliable. Construction management research is being firmly rooted within the positivist tradition. Dainty (2007) proposes "a more expansive outlook towards mixing methodologies and research paradigms could yield deeper insights into, and understanding of, the way that practitioners 'do' management in the construction sector (Dainty, 2008): p.9)."

Realism research philosophy also relates to scientific enquiry and is dependent on the idea of the objectivity of reality of the human mind. Walliman (2006) believes that realism is a type of epistemology approach since it do not prevent to change the society. As a branch of epistemology, this philosophy assumes a scientific approach to the development of knowledge (Walliman, 2017).

On the contrary, interpretive paradigm point out the difference between objects and humans (Dainty, 2008). The latter is suitable for social research due to its observations that are different depending on socialisation (Fellows and Liu, 2008). According to Saunders et al (2012), the interpretivist approach leads the researcher as a social actor to appreciate differences between different types of people (Saunders and Lewis, 2012).

8.2 RESEARCH STRATEGIES/APPROACH

8.2.1 QUANTITATIVE RESEARCH

Quantitative research seeks to gather factual data and to study the relationship between measurable facts and how such facts relate with previous theories and findings (Fellows and Liu, 2015). It is usually connected with positivism hypothesis-testing research being deductive. Quantitative research is useful to achieve literature review or collect data, nevertheless it is too superficial to understand the intrinsic causes of the subject taught.

8.2.2 QUALITATIVE RESEARCH

Qualitative research studies social phenomena within their natural setting, attempting to make sense of, or to interpret the phenomena in terms of the meanings it brings to them

(Lincoln and Denzin, 2003). It involves the use and collection of a variety of empirical materials such as a case study, personal experience, introspective, life story, interview, observational, historical, interaction and visual text, which describes routines, problematic moments and meanings in the life of an individual (Denzin and Lincoln, 1994).

The HBIM implementation presents issues that need to be explored further. HBIM research and its processes are suitable for using qualitative research (Creswell *et al.*, 2007).

8.2.3 MIXED METHODS/TRIANGULATION RESEARCH

Mixed method research uses quantitative and qualitative approaches within types of question, research methods, data collection and analysis procedures, and sometimes inference (Newman *et al.*, 2013).

The main advantages of this approach are the reliability and validity of the results and the greater definition of the phenomena in terms of description of the problem. However, the possible disadvantages are the cost of collecting data and the necessity of understanding a variety of data collection techniques (Yin, 2009). Mixed methods are traditionally used within social research but within the construction, management is becoming a widespread practice.

9 ANNEX 2. GRAPHIC ANNEX OF SAN JUAN CASE STUDY

As a result of San Juan case study it was developed a graphic heritage template for Revit software. The graphic results of San Juan case study where partially presented in the final report of San Juan case study (Jordán-Palomar and García Valldecabres, 2018) and in the master dissertation of the author (Jordán-Palomar, 2015). Both documents were written in Spanish.

- Situation floor plan
- General floor plan
- Floor plan s.XIX
- Floor plan S.XVII
- Floor plan S.XIV
- Floor plan S.XIII
- Section south
- Section north
- Section transversal
- Section West
- Section south s.XIV
- Section north s.XVII
- Section S.XIX
- Section west s.XIII
- Axonometries by phases
- Views by phases
- Virtual rendering

Jordán-Palomar, I., García-Valldecabres, J. (2018), San Juan case study report [*Caso de estudio del conjunto de San Juan del Hospital: informe final*] *Universitat Politècnica de València,* Universitat Politècnica de València, Valencia.

1. IGLESIA Y ANTIGUO HOSPITAL
2. ANTIGUOS HUERTOS
3. CASA DEL COMENDADOR
4. ESPACIO PARA RESIDENCIA DEL CLERO
5. CRIPTA
6. CAPILLA BARROCA DE SANTA BÁRBARA
7. CAPILLA FUNERARIA
8. PATIO SUR ANTIGUO CEMENTERIO MEDIEVAL
9. ANTIGUOS BAÑOS ÁRABES
10. ANTIGUO TORREÓN
11. ANTIGUA PUERTA Y MURALLA DE LA XEREA
12. PATIO NORTE

Planta de Situación

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Planta de Emplazamiento

0.04

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Planta Actualidad
1 : 150

0.05

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Planta Arqueología
1 : 150

0.06

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Planta s.XIX
1 : 150

0.07

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Planta s.XVII
1 : 150

0.08

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Planta s.XIV
1 : 150

0.09

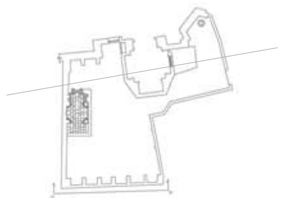
Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Planta s.XIII
1 : 150

0.10

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Sección Norte Actualidad
1 : 150



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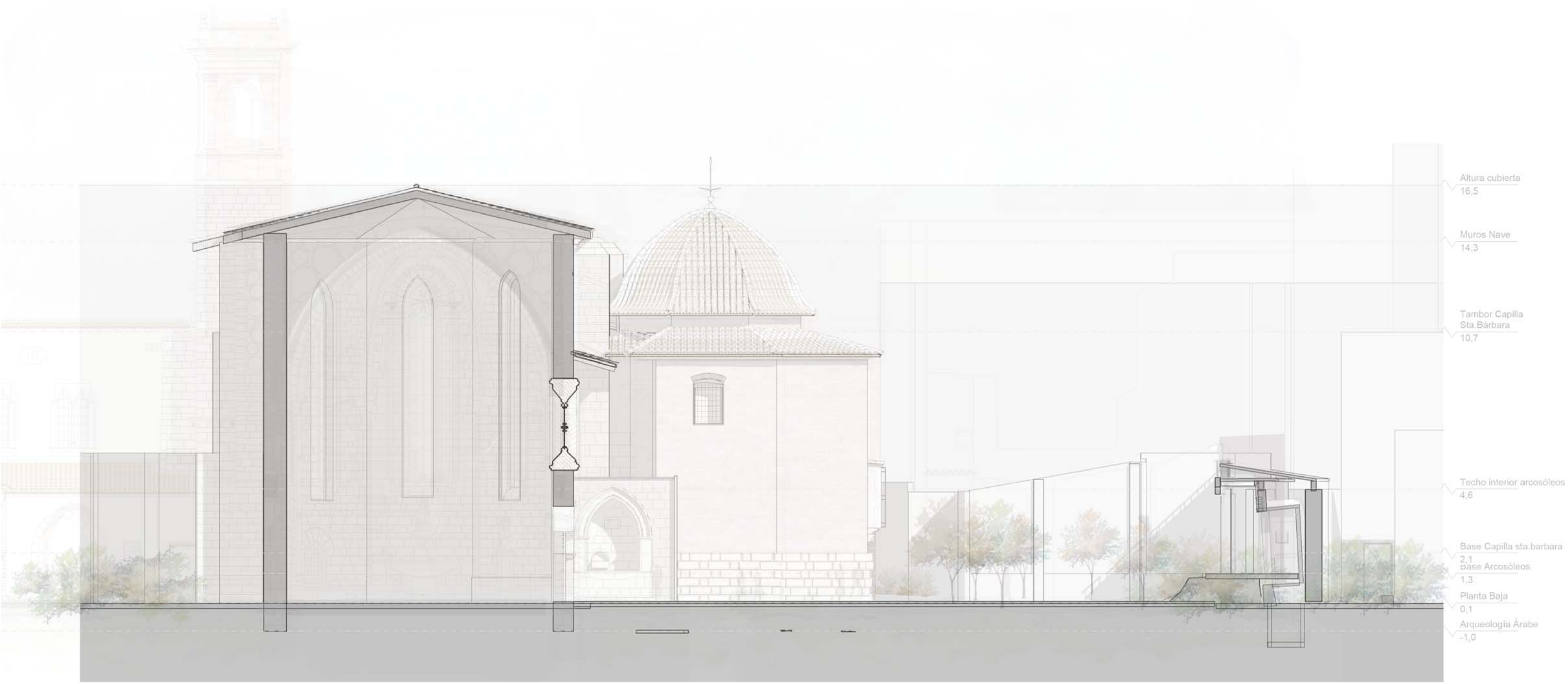
Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Sección Sur Actualidad
1 : 150



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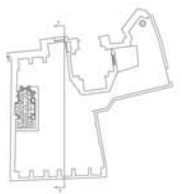
Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Sección Este Actualidad
1 : 150



Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

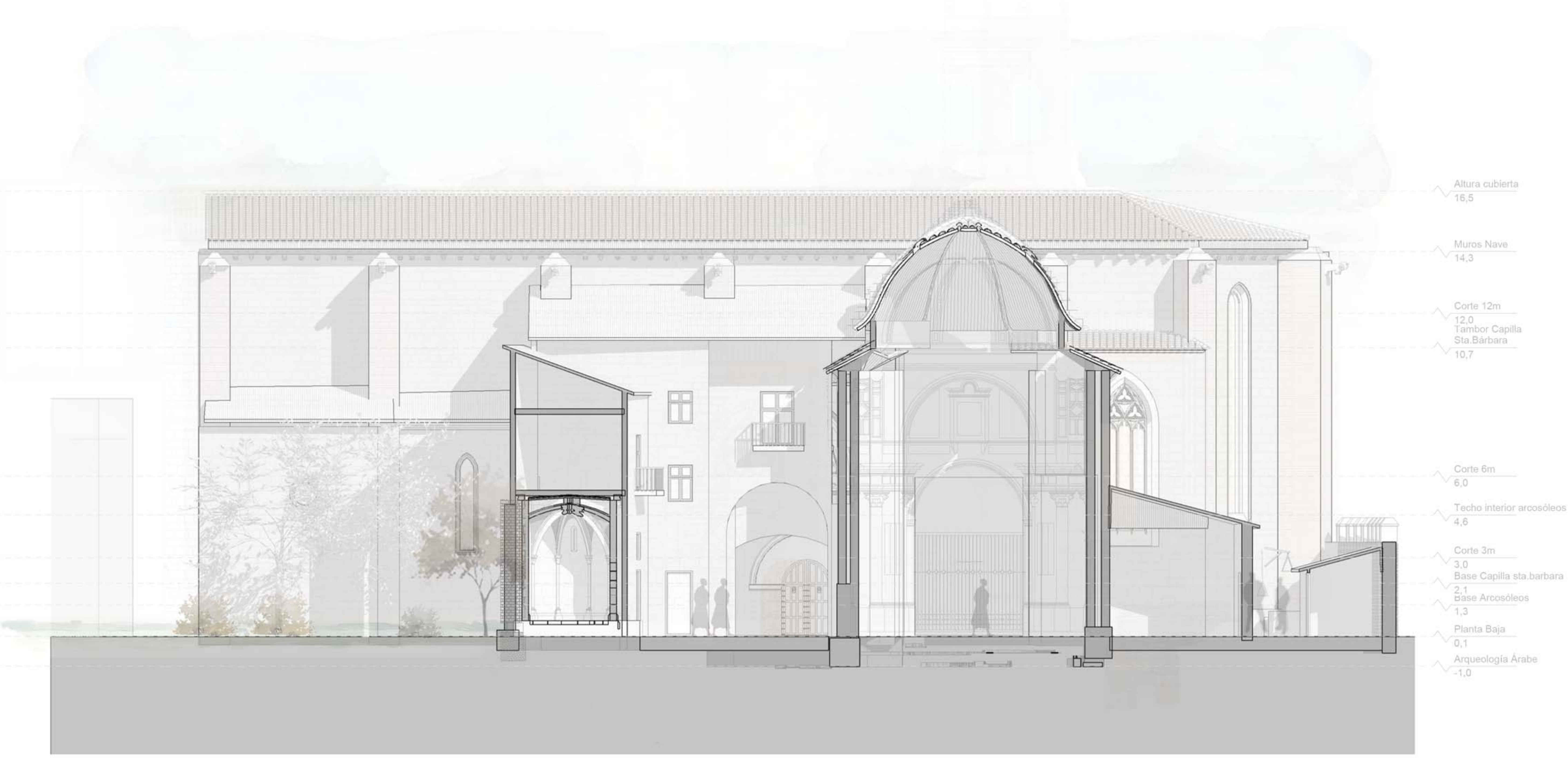
Sección Oeste Actualidad
1 : 150

0.14 Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Sección Oeste s.XIX
1 : 150

0.13 Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

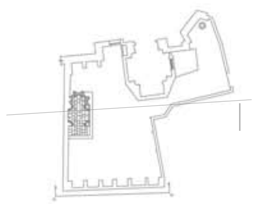
Sección Oeste Actualidad
1 : 150

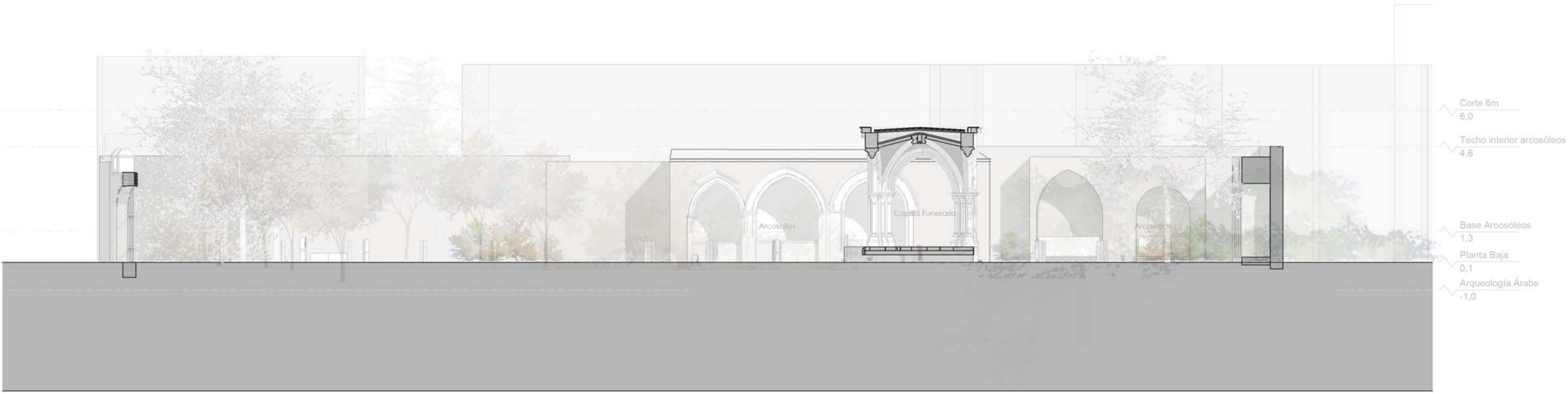


0.15

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Sección Norte s.XVII
1 : 150





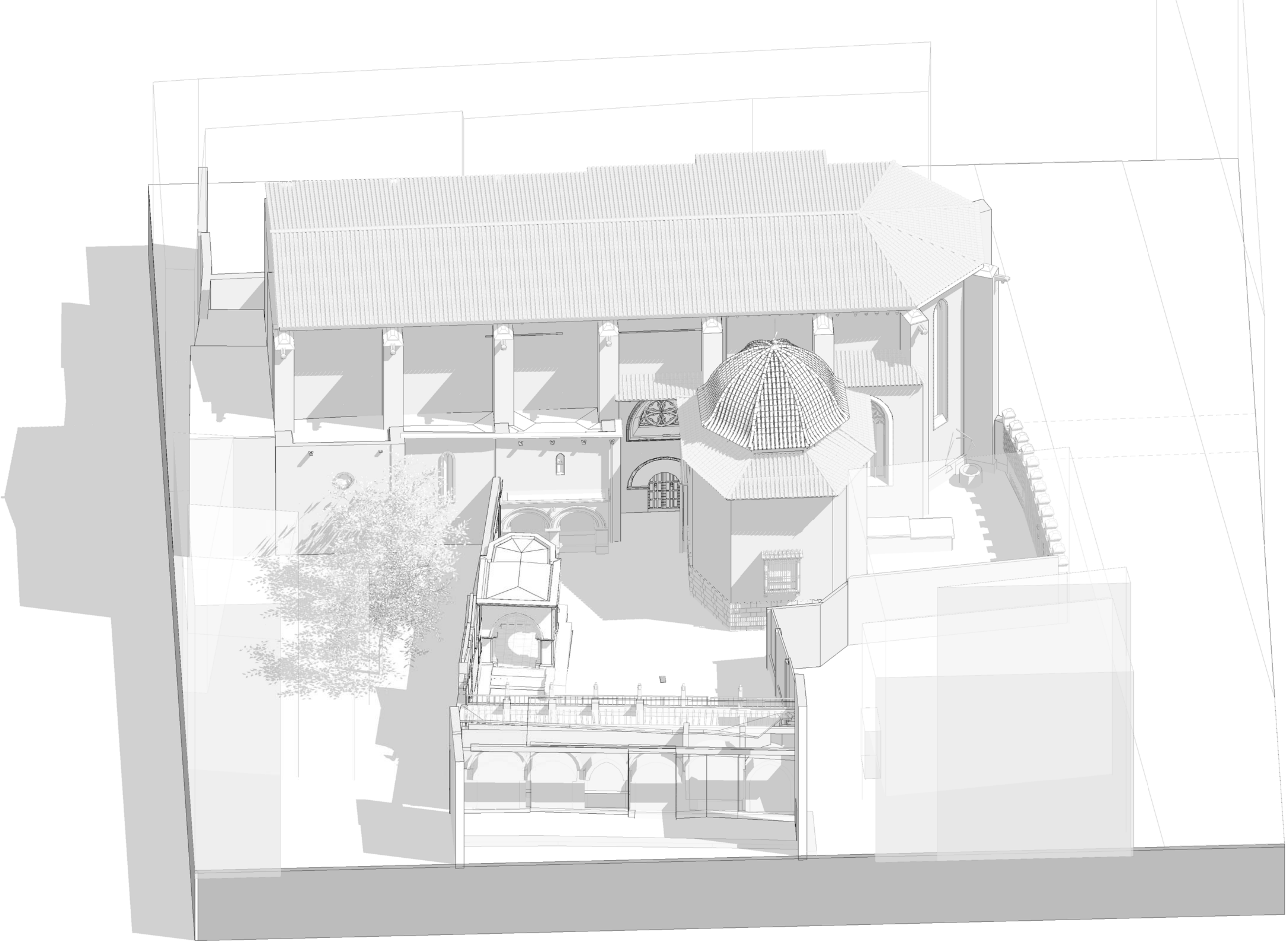
Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Sección sur s.XIV
1 : 150

0.17

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

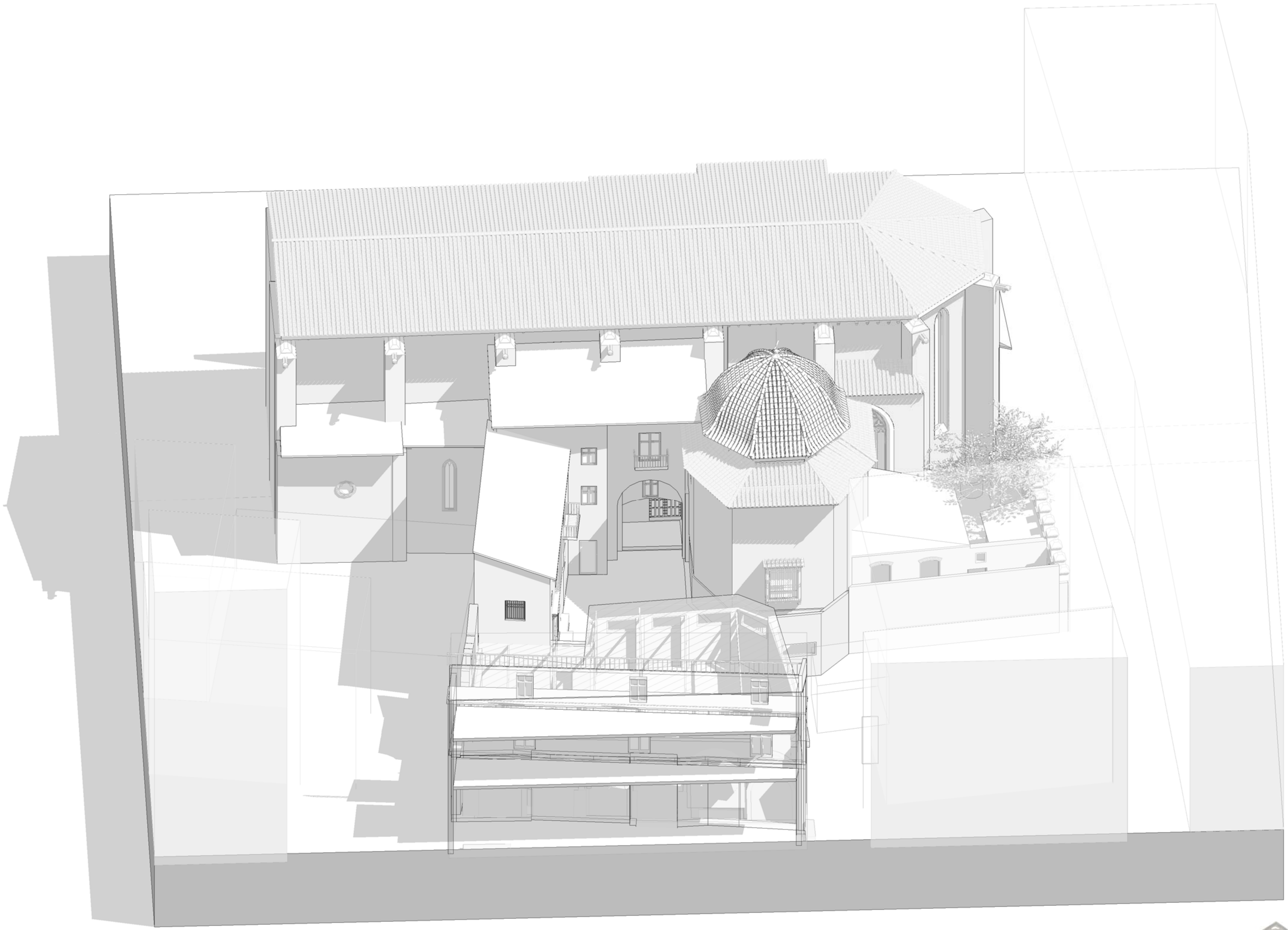
Sección Este s.XIII
1 : 150



0.18

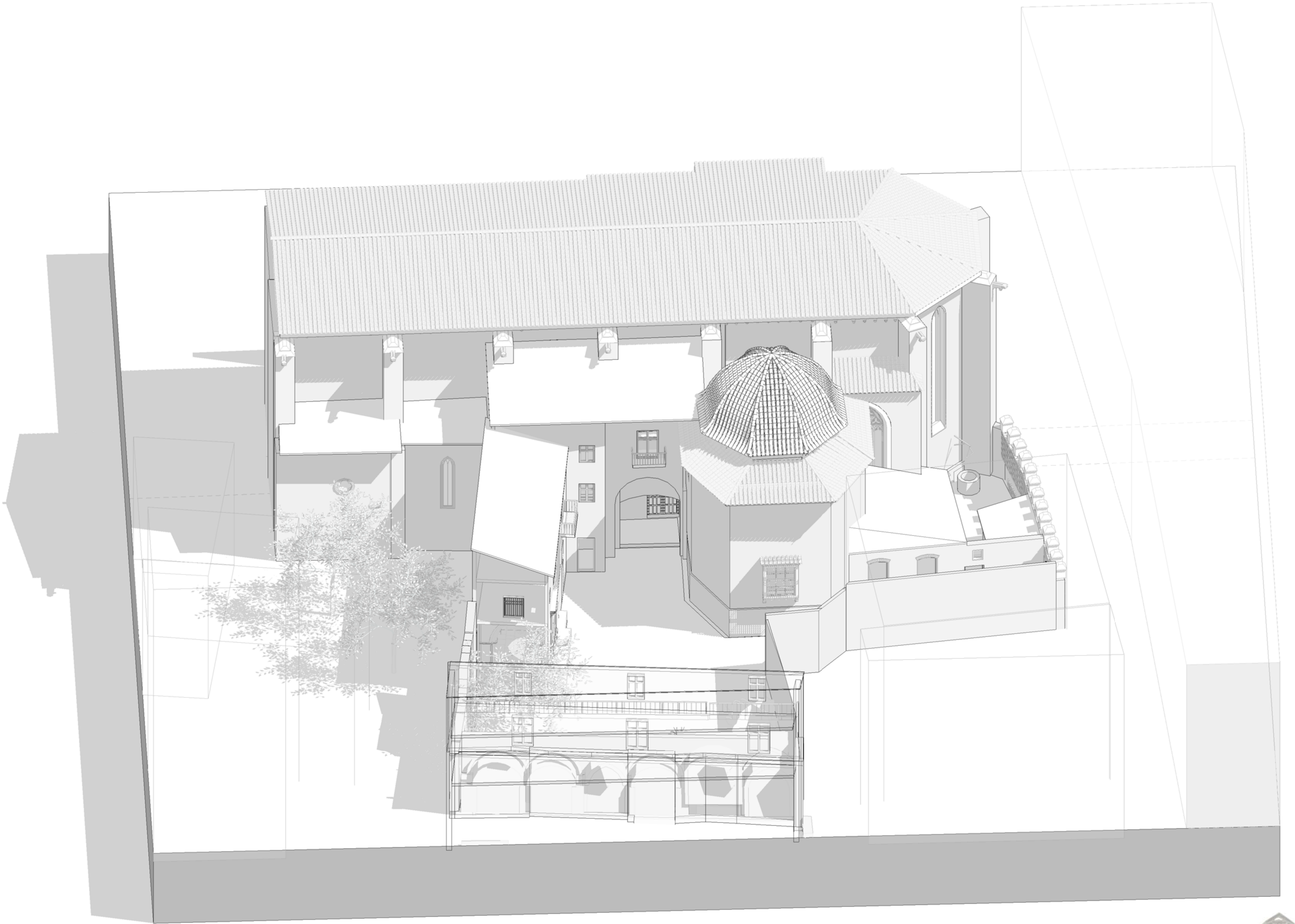
Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Axonometría Actualidad



0.19 Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Axonometría s.XIX



Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Axonometría s. XVII

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

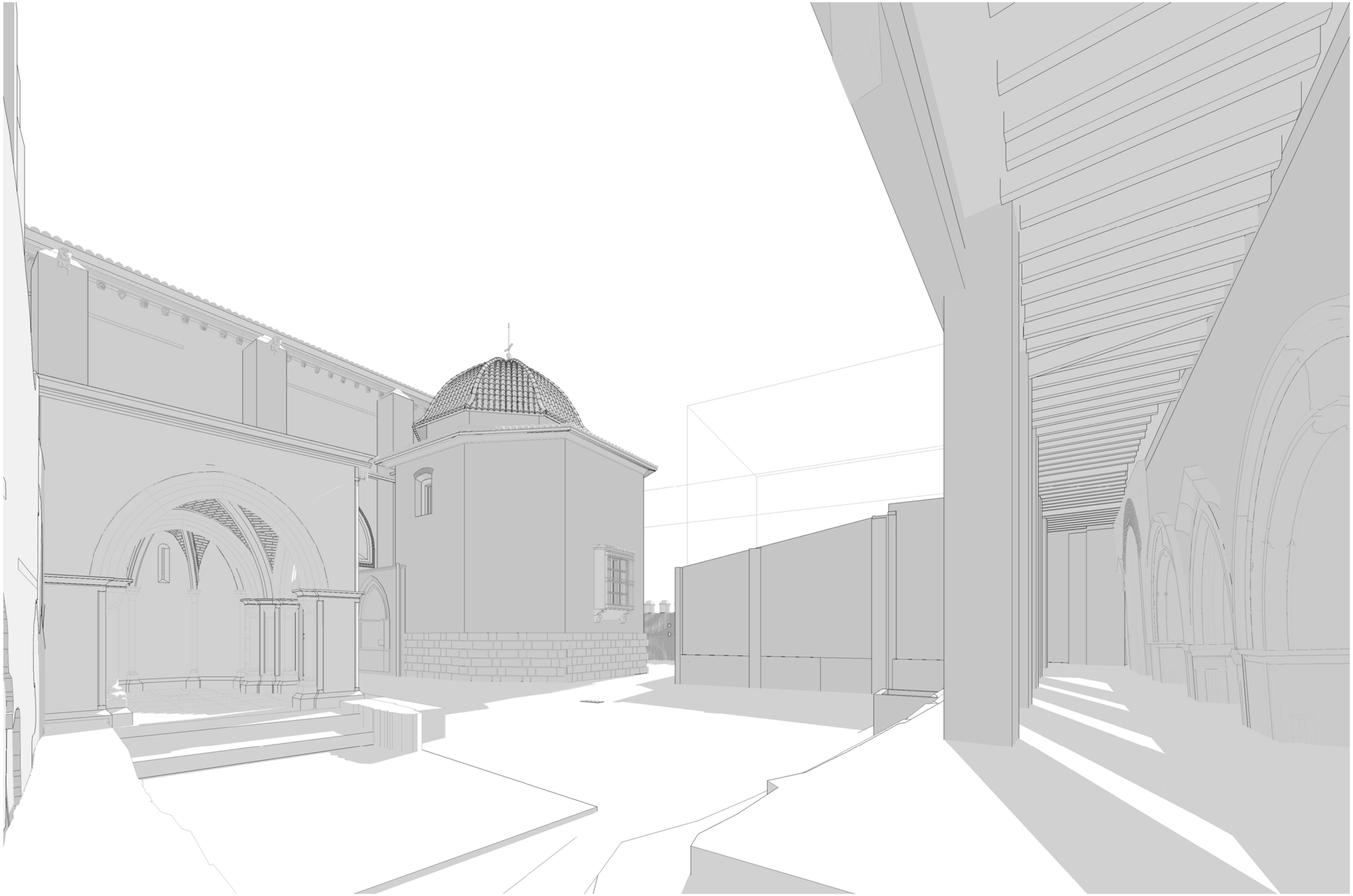
Axonometría s.XIV

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Axonometría s.XIII

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Vista Patio Sur Actualidad



Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Vista Norte Actualidad

0.25

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Vista Este actualidad

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Entrada al Patio Sur

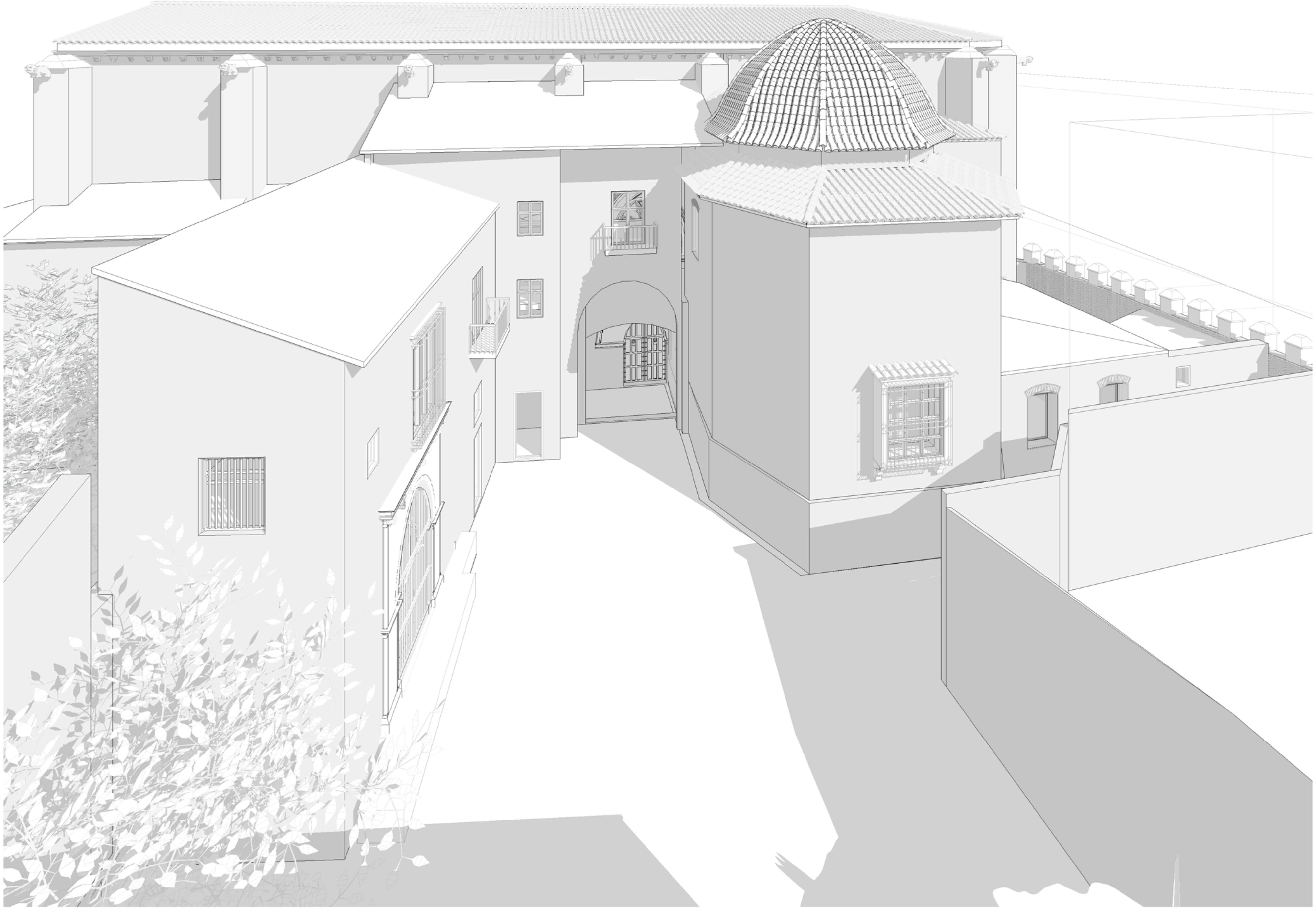
Vista desde la Calle Trinquete de Caballeros

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Vista del Patio Sur s.XIX

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Vista s. XVII



Vista del Patio Sur s.XVII

Patio Sur de San Juan del Hospital
Modelo de Gestión HBIM 12/06/2015
Isabel Jordán Palomar

Vista del Cementerio s.XIV

Vista del Cementerio s.XIII

10 ANNEX 3. QUALITATIVE DATA ANALYSIS USING NVIVO

Annex three shows the process to obtain and analyse data obtained through the semi-structured interviews, and the case studies. These techniques are considered inherent to qualitative research so it is because Nvivo was chosen as qualitative data tool (Robins and Eisen, 2017). Nvivo software is a qualitative scientific tool that helps researchers to generate affinity tables and diagrams. This computer tool substitutes the manual excel tables that academics use to do for qualitative research to group data of interest (Robins and Eisen, 2017). Handling qualitative data is not usually a step-by-step process. Instead, it tends to be an iterative process where exploring, coding, reflecting, and memorizing. The process to perform qualitative data analysis using Nvivo entailed the following steps:

1. Prepare the interview. A folders structure was generated to have an organised archive, Figure 116. The interviews were carefully prepared and archived in the folder "empty interviews". The participant consents were also archived in the folder "participant consents", Figure 116.

Figure 116. Folders organisation to perform qualitative analysis, 2017.

2. Perform the interview, focus group or workshop, which produced the data archived in the folder named "filled interviews", Figure 116.
3. Record the audio of the interview, focus group or workshop, which produced the data archived in the folder named "Audios", Figure 116.
4. Transcript the interview. The transcripts are Microsoft Word files archived in the "transcriptions" folder, Figure 116. There are tools to automatically transform audio files into text files, however, the audio quality was not optima and this option did not work. Thus, the audios were manually transcript into Microsoft word files, Figure 117.

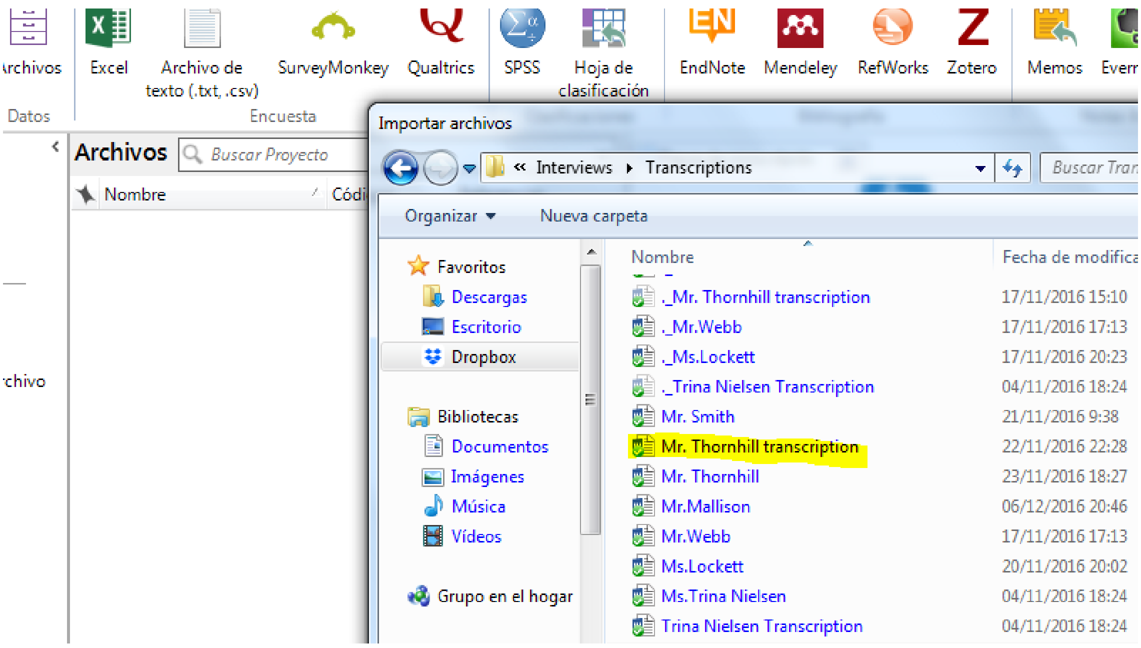
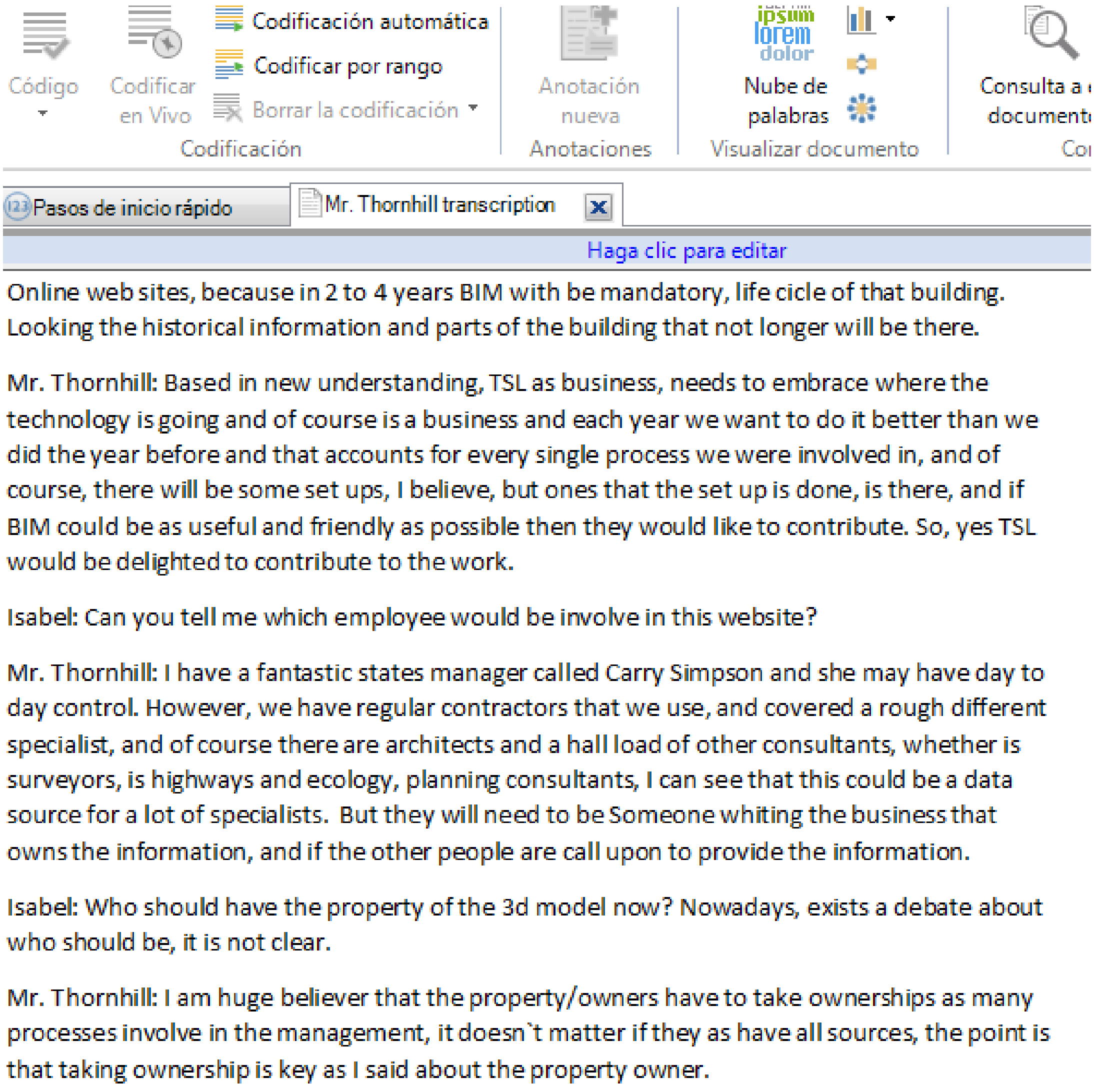


Figure 117. Importation of transcriptions into Nvivo, 2017

The audios were literally transcript in the Microsoft Word files, and then there were uploaded in Nvivo and cleaned to eliminate parts of the interviews that had no interest, such as comments not related with the topic or third people comments (a.e. assistants coming inside the room, private questions to the researcher). Figure 118 shows a cleaned transcription ones this cleaning process was fully performed.



Online web sites, because in 2 to 4 years BIM with be mandatory, life cicle of that building. Looking the historical information and parts of the building that not longer will be there.

Mr. Thornhill: Based in new understanding, TSL as business, needs to embrace where the technology is going and of course is a business and each year we want to do it better than we did the year before and that accounts for every single process we were involved in, and of course, there will be some set ups, I believe, but ones that the set up is done, is there, and if BIM could be as useful and friendly as possible then they would like to contribute. So, yes TSL would be delighted to contribute to the work.

Isabel: Can you tell me which employee would be involve in this website?

Mr. Thornhill: I have a fantastic states manager called Carry Simpson and she may have day to day control. However, we have regular contractors that we use, and covered a rough different specialist, and of course there are architects and a hall load of other consultants, whether is surveyors, is highways and ecology, planning consultants, I can see that this could be a data source for a lot of specialists. But they will need to be Someone whiting the business that owns the information, and if the other people are call upon to provide the information.

Isabel: Who should have the property of the 3d model now? Nowadays, exists a debate about who should be, it is not clear.

Mr. Thornhill: I am huge believer that the property/owners have to take ownerships as many processes involve in the management, it doesn`t matter if they as have all sources, the point is that taking ownership is key as I said about the property owner.

Figure 118. Clean transcriptions updated in Nvivo, 2017.

5. Import the word file into Nvivo 12 Pro version. As is showed in Figure 119, this software has multiple options of importation and it supports different importation extensions, such as OneNote, Outlook, Mendeley or EndNote. It is possible to link bibliography or classifications made with different software.

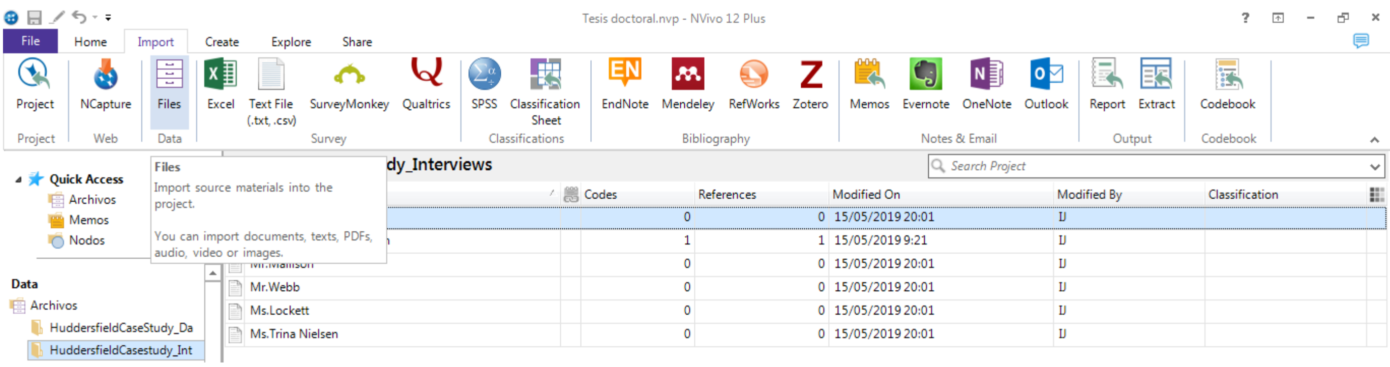


Figure 119. Importation of the transcription files into Nvivo, 2017.

6. Code the transcriptions by creating nodes.

To code the transcriptions it is necessary to understand what a code is and what a node is.

- Coding is the process of gathering related material together—and is a fundamental task in most qualitative projects. The process consist of generating ideas that can be repeated in different sources of information. Figure 120 shows the data source in the left part of the image and the nodes in the right part.
- A node is a collection of references about a specific theme, place, person or other area of interest. You gather the references by 'coding' sources such as interviews, focus groups, articles or survey results.

For example, while exploring sources (documents, datasets, pictures, video or audio) it could be coded any content related to 'non-tecnhical stakeholder's training' at the node non-technical stakeholders. Then when opening the node (by double-clicking it in List View, Figure 120) you can see all the references in one place. The nodes created in Nvivo ended up becoming the discussion topics in section 5 of this doctoral thesis.

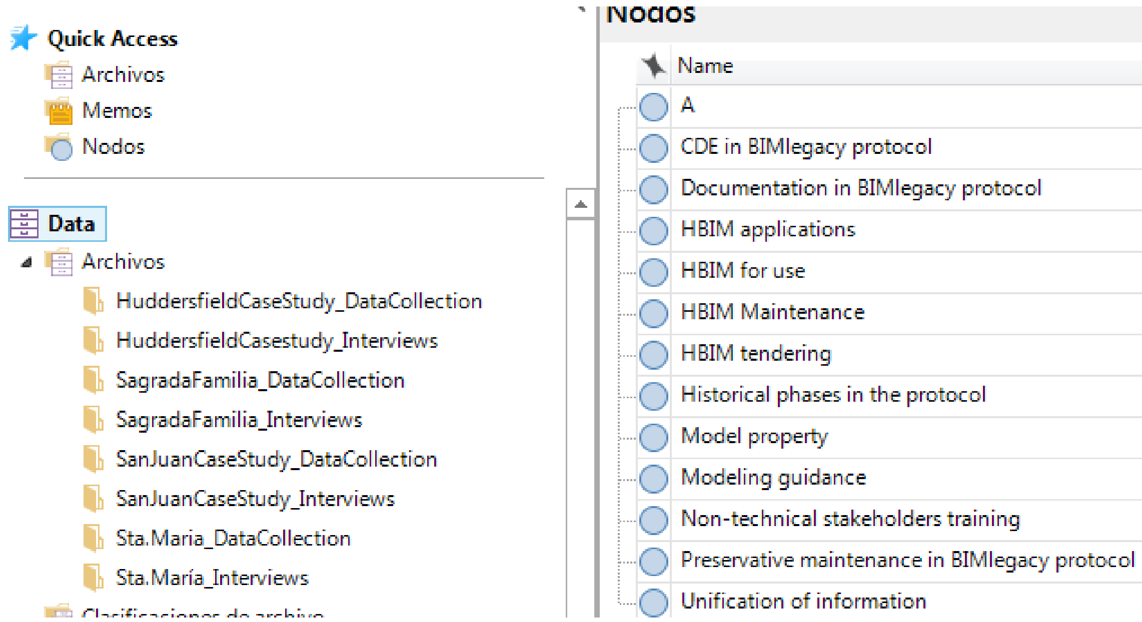


Figure 120. Generation of nodes, which are the same that the discussion topics in section 5, 2017.

The coding process was manual since the auto-coding was not reliable and some ideas were miscode through this process. The process consist of reading the transcriptions and assigning one idea or code to each sentence. It is quite easy to do by selecting the sentence and assign a code that represent its general idea. For example, a fragment of transcription of Fixby Hall case study:

> "Isabel: Which kind of information would you think could be interesting to have in a 3d model?
> Mr. Webb: I think that would be interesting to put how the rooms and the building has changed over the last probably 20 years"

The idea that Mr. Webb expressed is related with the node "Historical phases in BIMlegaycy" and it was presented as a BIMlegacy protocol benefit in the discussion section of this thesis because this idea was shared not just by Mr. Webb but by other participants, according to the results of the qualitative analysis with Nvivo. The process to assign codes to text fragments is illustrated in Figure 121.

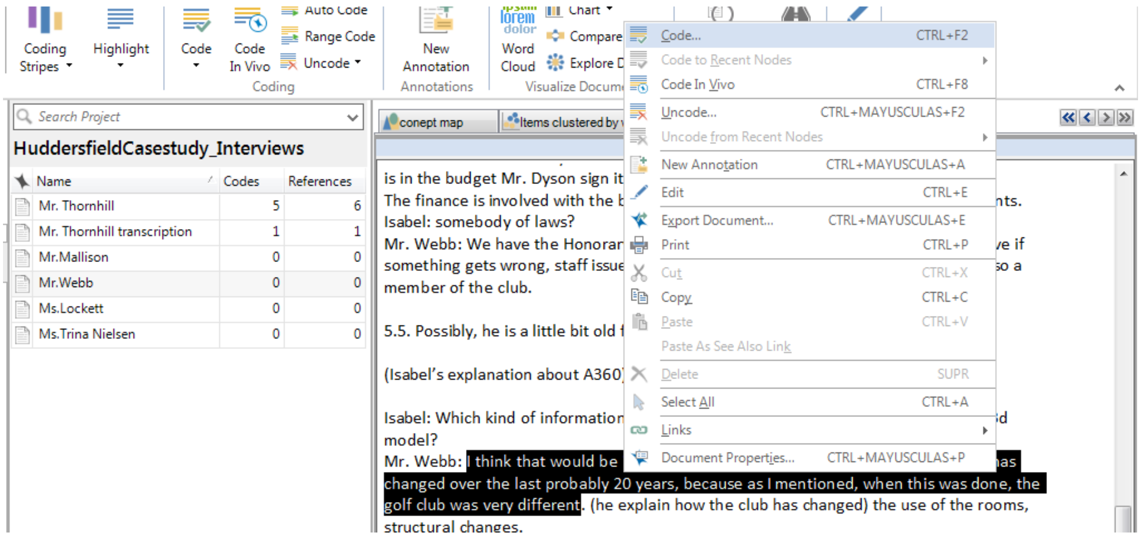


Figure 121. Process to assign codes in Nvivo, 2017.

In NVivo, a node is a virtual container that holds your coding. Nodes let you gather related material in one place so that you can look for emerging patterns and ideas. Figure 122 shows the fragments of text associated to each node.

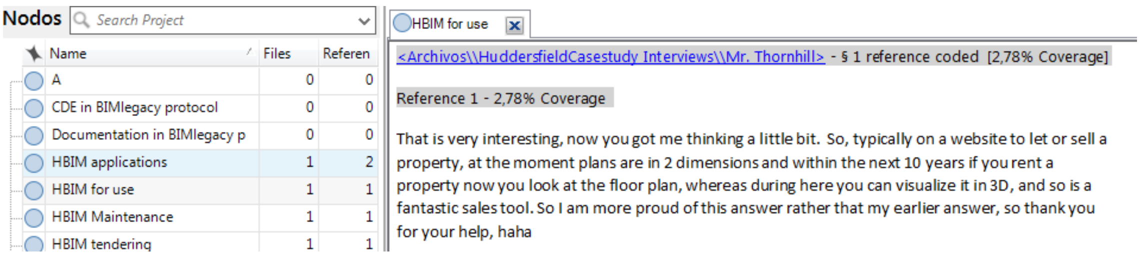


Figure 122. Fragments of texts associated to each node, 2017.

7. Create cases

Cases are people, places, organizations, events or other entities that represent the focus of the research. This investigation had few cases so the case nodes were created manually (one at a time). The cases that were created were just four: two by stakeholder's nature (BIM stakeholders, Non-technical stakeholders) and two by places (England and Spain).

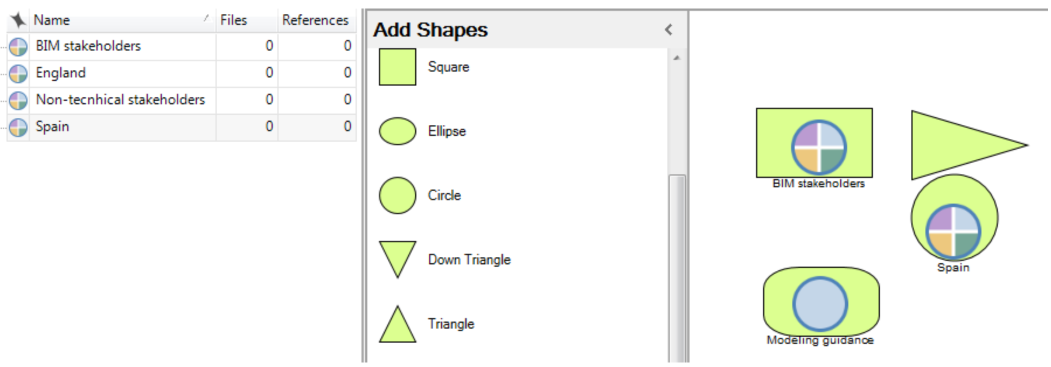


Figure 123. Shapes of Nvivo linking different codes, 2017.

The cases were translated into processes and diagrams by associating cases and nodes to the shapes of Nvivo, which is the first step to create the flowchart explained in the main text of this document, in section 4.1.5.

8. Analyse data using different tools of Nvivo: hierarchy chats, clustering, and word similarity.

To explore the results of the qualitative data analysis with Nvivo three different options were used (Figure 126):

- Charts such as “Hierarchy chart”.
- Maps such as “mind map” or “concept map”.
- Diagrams as “cluster analysis” or “comparison diagram”.

Those systems were used to visualise the results of the analysis and helped to understand the results of their analysis in a more measurable way.

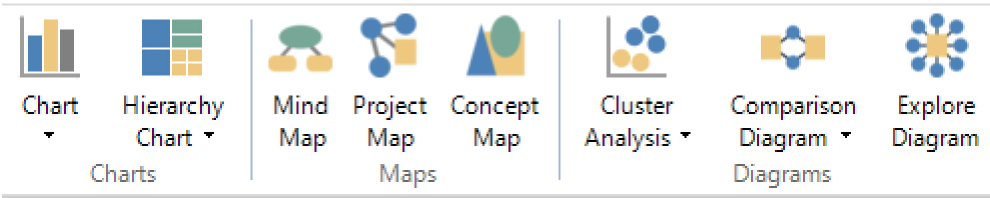


Figure 124. Options to explore the results of the qualitative data analysis, 2017.

The systems to visualise the results of this investigation are explained below:

i. Hierarchy charts

Hierarchy charts visualize a hierarchy, helping to see patterns in the coding or view the attribute values of cases and sources. This tool was very useful to represent quantitative data showing how many times the ideas emerged during the interviews or focus groups. With this tool was possible to affirm that “model property” was a very important issue in HBIM discipline since it emerged more than 20 times, Figure 125. Also it was a common issue in different locations because it emerged both in England and in Spain cases of Nvivo.

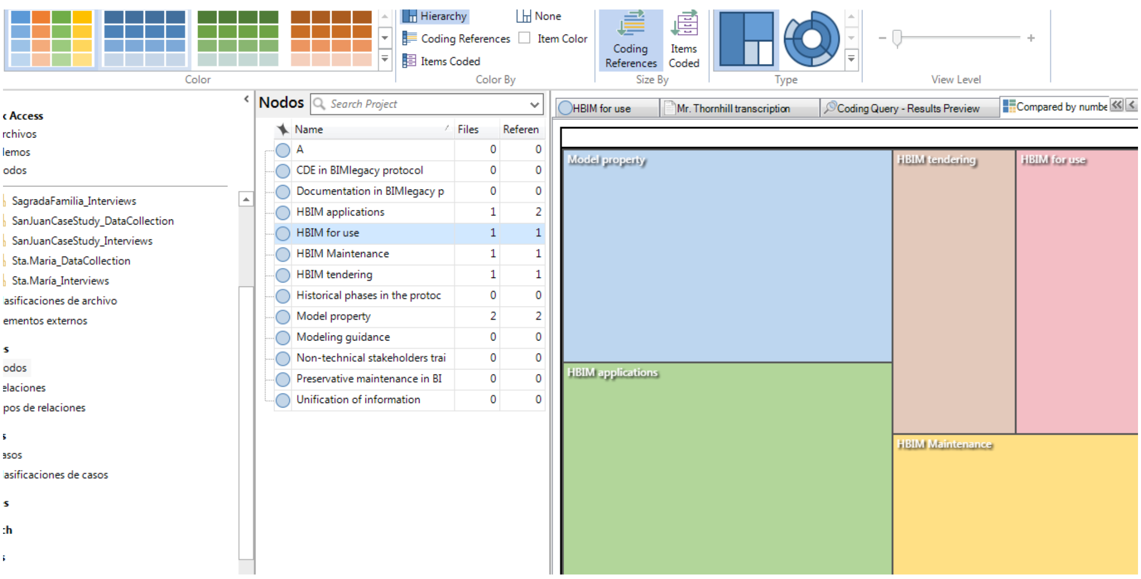


Figure 125. Hierarchy chart results after perform the classification case of Spain location, 2017.

ii. Comparison diagrams

Comparison diagrams were useful tool for comparing the similarities and differences between two project items. They can show the more relevant topics for a stakeholder according to the analysis of the interviews and focus group, Figure 126.

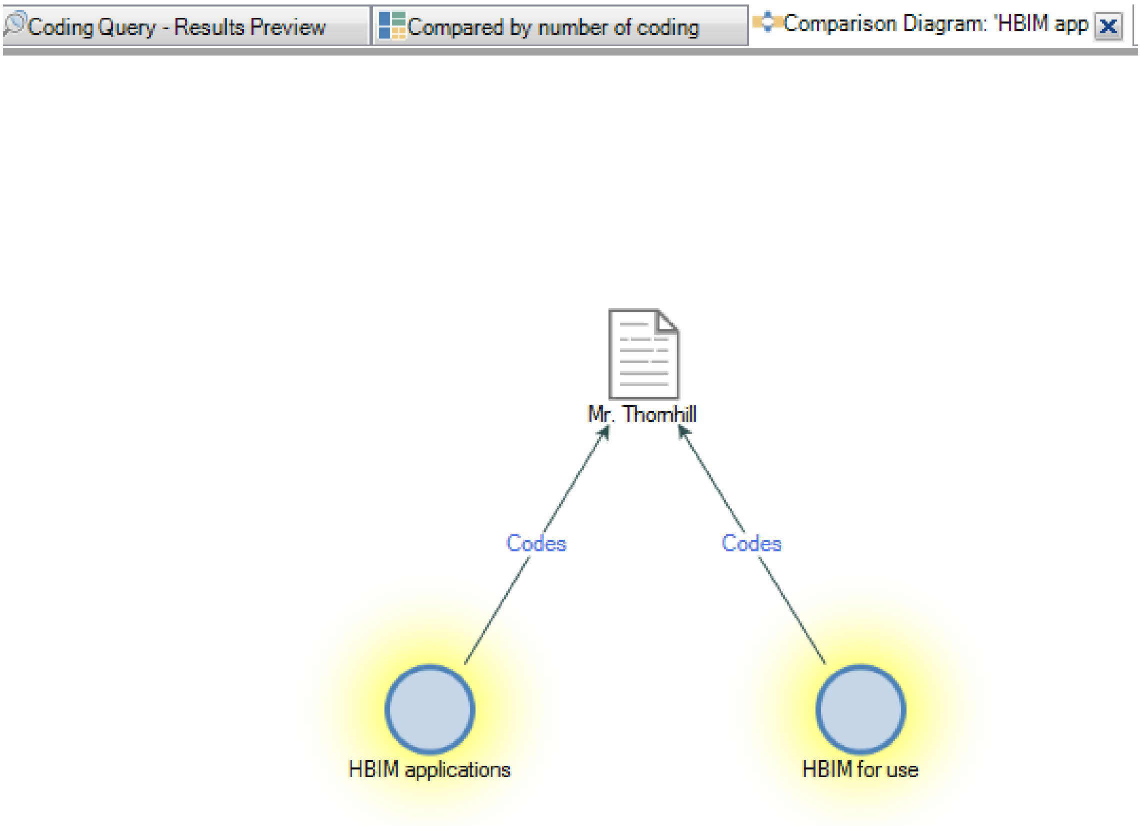


Figure 126. Comparison diagram created to relate stakeholders with nodes, 2017.

Another tool used to explore the results of the qualitative data analysis with Nvivo was exploring the cluster analysis relating the tree relationship of the nodes and codes. Figure 127 is a cluster analysis map that relates nodes and codes by word similarity.

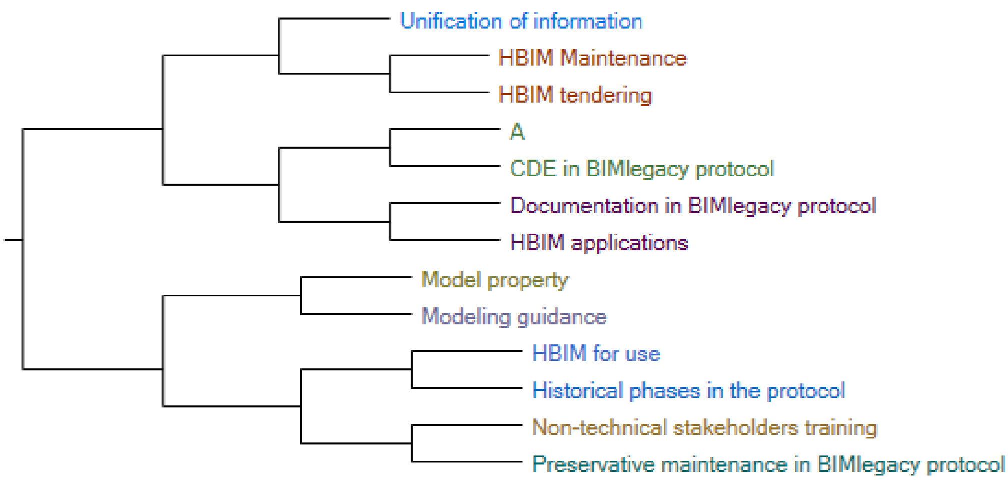


Figure 127. Nodes Map created as a result of a cluster analysis with Nvivo, 2017.

iii. Mind map

It was very useful to generate mind maps to understand the benefits and issues of the artefacts created. Mind map is a visual representation of hierarchical information that includes a central idea surrounded by connected branches of associated topics. As an example of these mind maps, Figure 128 shows the benefits of BIMlegacy platform according to the analysis of the data obtained in the case studies. It represents the most important benefits in the centre of the graphic and the secondary benefits in the sides of the circle. Thus, it was possible to conclude that the most significate benefit of BIMlegacy platform is to be a Common Data Environment (CDE) for heritage projects.

Figure 128. Mind map of the benefits of BIMlegacy platform, 2017.