Renovation of Heritage Assets using BIM: a Case Study of the Durham Cathedral

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Abstract

Heritage asset renovation is a major construction market in Europe. It traditionally involves processes of condition surveys and inspection, generation of current/proposed 2D/3D models, scenarios planning, supply chain management, construction planning, etc. This is a very slow and costly process and requires major rethinking and innovation. This paper aims to explore radical solutions to the renovation process through the development and adoption of BIM-based workflow processes and technologies. A case study of renovating the famous Durham Cathedral has been used to explore the aim of this research. The proposed workflow started with laser scanning to capture the interior of the church. Then a 3D model of the asset was developed to provide accurate information on the current state and layout of the building as a single accessible reliable resource, which had previously been lacking. The model provided a range of functions such as scenario planning and mobile virtual tours which were difficult to achieve with the traditional pre-BIM workflow. Condition surveys interlinked with the model were created, along with maintenance schedules for the team, which may provide time and cost savings compared to the traditional maintenance procedures. The finished model provided the Cathedral with a potential new digital tool-kit for understanding and managing the building more efficiently and for the preservation and maintenance by future generations, thus highlighting an important role of BIM in this significant sector.

KEYWORDS: BIM, Facilities Management, Heritage, Asset Renovation

1. Introduction: Heritage Conservation and Renovation

Historic assets are unique in nature, and are more than just physical entities. They hold universal value to all humanity and have a legacy for generations to come. Heritage sites contribute to the local communities and the wider economy, shaping the culture and conditions of the neighboring regions. Heritage tourism in the UK provided £5.1bn in economic output as well as 134,000 direct jobs in 2011, with figures steadily increasing over time. It also represents a significant source of demand for construction. It is estimated that the repair and maintenance of historic assets supported 180,000 jobs and generated economic output of around £4.1bn in the UK in 2010 (Heritage Counts 2014). The importance of heritage sites led to the formation of dedicated heritage groups/authorities operating at provincial or government levels, for the restoration and preservation of these invaluable assets and landscapes (XS CAD Limited, 2014).

The redevelopment and restoration of heritage assets entails a unique set of challenges, as one of the most crucial facets of the process is to preserve the structure's symbolic and cultural elements (XS CAD Limited 2014). It has special sets of requirements for the conservation, planning and construction of the assets, in addition to the complex funding and approval processes. Specialist knowledge and in-depth understanding of the asset and its history is needed for the renovation process, as a heritage asset carries multi-layered information beyond physical features. This requires an integrated representation of various types of information for the planning, decision-making and implementing the restoration (Saygi et al 2013). This process is greatly affected by the information available about the heritage asset and its judgmental evaluation by experts. Hence, this paper explores the hypothesis that BIM can facilitate the planning and implementation processes involved in the renovation of heritage assets.

1.1. Literature Review

Renovation work of existing buildings, including heritage assets represent the largest proportion of construction work. It is estimated that only 2% of construction work per year is in newly built assets (Kincaid 2004). The costs of operating and maintaining an asset during its lifecycle outweigh the initial capital expenditure. Therefore, significant additional improvements in value, cost and carbon performance can be potentially be derived from the use of BIM for existing building works.
BIM is not limited to the mainstream AEC (Architecture, Engineering and Construction) sector, but can also be implemented on historic renovation projects and the heritage conservation field. Indeed, studies and applications in this field are becoming increasingly available in recent years. Saygi et al. (2013) explored the roles of BIM in the conceptualization, structuring and representation of architectural heritage data, and demonstrating that a better understanding for both tangible and intangible features of the heritage objects can be achieved through BIM. D'Annibale et al. (2013) examined several workflows of surveying and documenting built assets and compares the different approaches. The findings demonstrate that the optimum approach is determined by several factors such as cost, desired accuracy and availability of the appropriate resources for each specific case. Bianco et al. (2013) implemented a BIM-based database of architectural heritage using the stone architecture between Italy and Spain. The exchange of information, works across interdisciplinary teams and documentation is facilitated through the use of laser scanning and 3D modelling software on the heritage site (Bianco, I. et al., 2013). For historic buildings, the proposed method can provide an accurate record of the 3D conditions before, during and after renovation as well as monitor the quality of the works. The BIM model can be used after the restoration for management and maintenance of the building (Wu, T.C. et al 2013). Utilizing the parametric components inherent in BIM tools enables recording the specific materials and methods related to historic objects to be used for restoration, in a format that makes it conveniently accessible for future conservation (Fai, S. et al 2013). Both the BIModel and the ontologies within enable improved communication among professionals who collaborate during the preservation processes, as it allows them to clearly interpret and use the information in the centralized hub for their purposes (Di Mascio, D. et al 2013). To date the prior studies on adopting BIM in historical building applications have been mainly either theoretical or focused on virtual representation and documentation. A considerable proportion of the public remains unaware of the full potential that BIM can offer in aiding the conservation of historical assets and facilitating all the functionalities encompassed. The purpose of this research will be based on this gap in literature and current practices around historical asset renovation.

1.3 Purpose of the research

This paper explores the renovation of historic assets, investigating the role that BIM can play in making the process more efficient and the functions that it can fulfil. It compares between BIM-based and traditional workflows and explores the benefits, challenges and limitations of each approach. The renovation of the famous Durham Cathedral will be used as a case study, where the Cathedral's Chapter House was used as a pilot project to demonstrate the value of BIM.

1.4 Traditional Workflow of Heritage Asset Renovation

There are rigorous standards for the preservation activities of heritage assets. Any alterations must not affect the authenticity and integrity of the asset, requiring careful justification. Therefore comprehensive information needs to be documented and available to understand the impacts of the activity and to preserve the materials, features and spatial relationships within the building (English Heritage 2008).

The original restoration process of the building is very labor-intensive and costly, which is impacted by budget constraints. A typical process to restore a mason brick is to, first physically survey stone conditions, identify a brick that needs repair, take a photograph which would be printed off and physically attached to a document. In order to examine the stone more closely, scaffolding would be needed, which could potentially damage the sensitive site. The stonemason then has a closer look at the stone, take measurements and determine the material, and after obtaining this information, procure the necessary material in order to actually restore the stone. Finally, the architect would examine the finished brick, take measurements and document the change. It involves several parties and spans across a large time period causing disturbances thus, resulting in onerous and costly process. Traditionally, heritage assets employ a very basic Computer-Aided Facility Management (CAFM) system to support the facilities management activities. Such a system is also disconnected from the previously illustrated process and changes are documented manually.

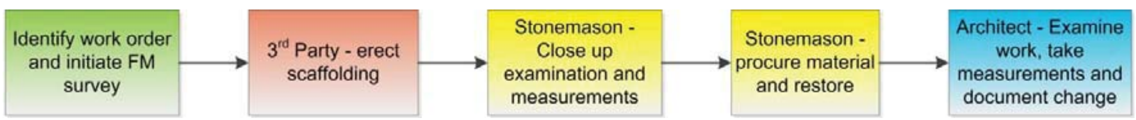

Figure 1 Traditional workflow for stone

2. Case Study: Durham Castle and Cathedral

2.1. Historical Context

The Cathedral was built in 1093, in the city of Durham, England, originally for a community of Benedictine monks. Durham Castle housed the shrine of St Cuthbert, and served a political and military function by supporting the authority of the prince-bishops over England's northern border. The site possesses some of the most intact remaining monastic buildings in England, and regarded as one of the finest examples of Norman architecture (Durham Cathedral 2015).

The current cost to maintain the cathedral is *£60,000 per week. It holds over 1700 services a year and receives over half a million of visitors each year. It has been in continuous use since its original construction 900 years ago and it remains a place of worship and pilgrimage as well as an important visitor attraction (*Durham World Heritage Site 2015).

2.2. Renovation Project

Durham Cathedral does not charge entry for visitors. Conversely, it is expensive to run and costs in excess of £3.3m annually to maintain (Durham World Heritage Site 2015).

The newly hired Cathedral's facility manager, who has previous experience of using modelling tools, encouraged the change from the current workflow of maintaining the buildings to decrease the renovation and maintenance costs and make the process more efficient and financially sustainable.

Figure 2 Durham Cathedral's stone vault (Durham Cathedral and Jarrold Printing, 2015)

It was chosen to investigate BIM as a methodology to achieve efficiencies by supporting the transition from traditional facility management procedures to a process that utilizes digital information and 3D models to deliver greater value.

Initially, the proposal was to create a BIModel for the entire Cathedral, which was later regarded as unfeasible for that moment in time. Therefore, the Cathedral's Chapter House room was chosen to be a pilot project to demonstrate the BIM process and its potential benefits, which, if successful, could be potentially carried on to the rest of Durham Cathedral. The Chapter House was chosen to be modelled as it is not open to the public and will not disrupt the current activities at the Cathedral. Durham Cathedral's teams initially proposed to laser scan the Cathedral and create a 3D model of the room. The research team then utilized the model to demonstrate the functions that BIM can support and the benefits that can be achieved for the restoration process and the future maintenance of the facilities.

Reliance is placed on architectural drawings dating from the last century and others on linen from the 1800s as a base for decision making and assessment of the state of The Chapter House. There are large amount of documents and pdfs which are frequently inaccurate and often misplaced. There is no searchable way of accessing the information and lack of indexing. As a result, architects and contractors had to be paid to make bespoke studies. Also due to the lack of information about the structure's build-up, unless intrusive surveying was undertaken, it was difficult to determine typical measurements such as thickness and volume that are needed for the restoration process.

2.3. Laser Scanning and Point Cloud Creation

The first step was to capture as-built conditions of the Durham Cathedral prior to starting the modelling process. 3D Laser scanning was chosen as the method to survey the building. Scanners can differ in: scan radius, scanning speed, accuracy of the scan as well as the weight/portability, but mostly work on the same principal. A laser scanner emits a rapidly pulsing or continuous laser beam towards the area being scanned. The laser scanning unit distributes the laser beam both vertically and horizontally, resulting in a systematic sweeping of the beam over the surrounding area. When a beam hits surrounding objects, some of the energy bounces back to the scanner, where if the returned energy signal is strong enough, the unit detects it and a timer uses it to calculate the distance from the scanner to the object. For each distance measurement, the corresponding horizontal and vertical angels of the rotating laser are calculated and used to acquire precise 3D X, Y and Z coordinate positions for each point.
To add texture and color to the scan, photos are taken using built-in or external cameras and then merged with the scanned data. If the area to be scanned is greater than the unit's range, or for views that are obstructed due to site logistics, the scanner is moved to different vantage points for more scans. The result is a collection of individual scans, which need to be linked together to create a single representation of the entire scene called a Point Cloud. This can be done on-field by using scan targets around the site, which when located in each scan, are linked together in the software. Some newer methods are done all within the software, which needs to identify a certain percentage of overlap with the previous scan, and then automatically links to register them in an intelligent

way. Prior to starting the laser scan process, appropriate calibration of the unit needs to be undertaken to maintain maximum accuracy. The unit used for Durham Cathedral had an overall tolerance of ± 50 millimeters, which was very adequate for the accuracy of subsequent 3D modelling. Some areas of Durham Cathedral such as the tight circular staircase were hard to access with the laser scanner. However, more versatile and less expensive handheld scanners could have been used in this area but this would have affected the accuracy of the scan, the size of the object being scanned and the time to complete the scan. The resulting scan of the Cathedral was a 250 million point scan that resulted in a model size of 8 gigabyte and highly accurate measurements of the site (typically to a few millimeters), as well as a record of the intricate detail of the site's current condition (Figure 3). However, this is simply a detailed 'dumb' 3D representation, which needs to be enriched with information to become an intelligent model that supports decision making of the asset renovation.

Figure 3 Point Cloud of Durham Cathedral's grounds

Currently a key issue that is hindering the wider adoption of laser scanning is the cost of the scanners, with the bigger units costing tens of thousands, making it difficult for firms to purchase and use in-house (AEC Magazine 2015). The scanning process as well as the conversion of the Point Cloud model in an object based BIModel requires skills that many organizations do not possess in house. There are other methods of surveying the building such as photogrammetry, a technique where measurements are derived from photographs; however there are a number of practical and technical considerations that should be taken into account when choosing a surveying method (Ratcliffe & Myres 2006). A full cost/benefit analysis is beyond the scope of this paper and is dependent on site and personnel specific factors as well as the target application.

2.4. Creation of the BIM Model

Prior to modelling, the Point Cloud was then imported to Autodesk Recap, where it was manually purged to eliminate their interference, leaving only the room. The Recap model was then linked into Autodesk Revit, where the procedure of creating the geometric model was through tracing over the Point Cloud. For modern buildings, the standard modelling tools can be used to quickly create objects such as straight walls/ceilings with the object-specific parameters embedded. However this was not always possible in historic buildings due to the unique nature of the heritage assets. The examined building has irregular shapes and standard modern tools cannot be used to accurately represent its slanted structures. Therefore, the Generic Model tool was used for those areas, which allowed the creation of bespoke components that are as realistic as possible, and then manually adding any object-specific parameters to it. The choice of whether or not to use the Generic Model tool can be determined by the future use of the model. If it is for purposes that do not require high-accuracy representations, then the standard tools could suffice which are less time consuming. After creating the geometry which defines the structure, the model was populated with parametric data resulting in a data-rich 'intelligent' model. This included condition information of the structure and traditional outputs such as elevations, sections and floor plans (Figure 4).

Figure 4 3D model created from Point Cloud scans

2.5. Issues and Challenges

The Chapter House was not surveyed before and there were no documented measurements of the structure. Therefore, the modelling was based solely on the Point Cloud. The use of the Point Cloud as a basis for creating the 3D model brings its own set of challenges. The presence of instruments or stray equipment on site can cause problems in defining the building. This can be resolved by either manually purging the instruments prior to modelling or clearing the site prior to scanning. However, it may be beneficial at times to leave the equipment to see where the objects meet and gain more information on the building's structure.

The Point Cloud can have sometimes gaps and either lack points or appear grainy. This could be caused by the lack of view during scanning (e.g. site logistic issues) or the laser scanner's specifications such as capacity, accuracy and range of scanning. In these circumstances experienced surveyors and modelers use the surrounding structures and patterns as a reference. As Point Cloud points from different scans overlap, it can be difficult to get a clear view causing lines to be drawn over the wrong points. Isolating Point Cloud sections could provide a better view to reduce error. Due to the uniqueness of this case study and lack of uniformity, the use of catalyst tools to accelerate the modelling was limited. As an example, in modern buildings, where columns may be of a standard size and evenly spaced, they could be quickly arrayed with a specified width. But for historic buildings, it has to be taken case by case due to the non-uniform widths and distances.

The process of scanning the building and creating the Point Cloud took approximately 2 days. However scanning time can be reduced by using faster laser scanners. It took 15 days to create the BIModel of The Chapter House, which consisted of 3 days to understand and plan the task, 10 days for modelling and 2 days for adding parameters and creating the different templates, filters and walkthroughs. However, there was a substantial learning curve as the Point Cloud to Revit process was unfamiliar. If the project was to be done for the entire Cathedral, the process would not benefit from repetition and duplication as historic buildings are unique and problem solving would be needed during modelling for each area.

After the model has been completed and setup with the necessary parameters, maintaining the model in the future is a manageable task for the facilities management and it requires minimal training on tasks such as updating values in the database or the model. However, major changes and works in future will still need to be updated by an architect or consultant. Autodesk Revit is not necessarily required by the client as the model could be a basis for a database system and can be viewed either by an FM integrator tool or one of the free BIM viewers available. Durham Cathedral would need capable hardware to run the software, with some basic navigational and function specific training.

2.6. BIM-based Process

After the model was completed, it was showcased to Durham Cathedral's facility management team. A discussion around the BIModel, the workflow and the BIM functionalities identified the following advantages:

- Provided accurate information of the current state and layout of the building as a single, accessible and reliable resource that will reduce the physical record collection.
- Decreased the need to undertake expensive, time-consuming and potentially intrusive surveying as well as reducing the human error associated with such a process.
- Enabled traditional outputs such as sections, floor plans and elevations as well the dimensions and volumes of ceilings and walls to be produced at no additional cost and within seconds, without any intrusive or damaging techniques. These outputs can be used by the supply chain for the restoration works.

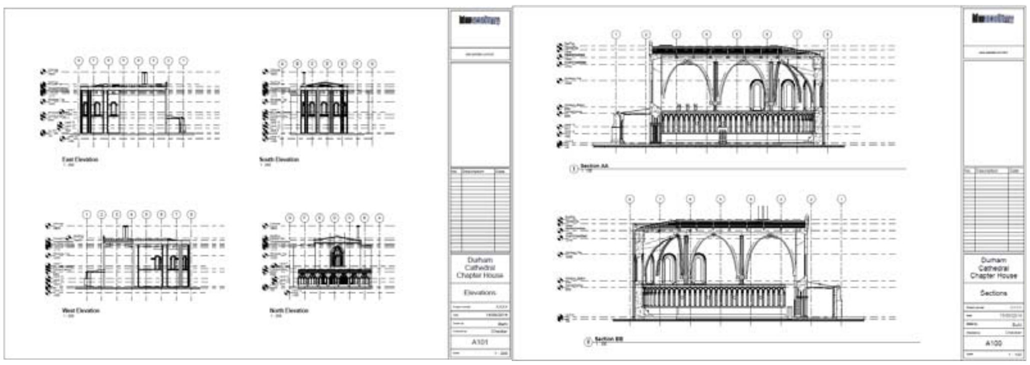

Figure 5 Traditional outputs such as sections produced from the model

- Added bespoke parameters including the condition of elements interlinked with the BIModel with a set colour for each parameter value denoting the severity of the condition and the urgency of repair work e.g. 'A: severe condition'; 'C: minor condition, '1: urgent' and '3: low priority'. This could be used as a planning tool for the restoration of the stone works, and as a visual aid tool for locating objects.

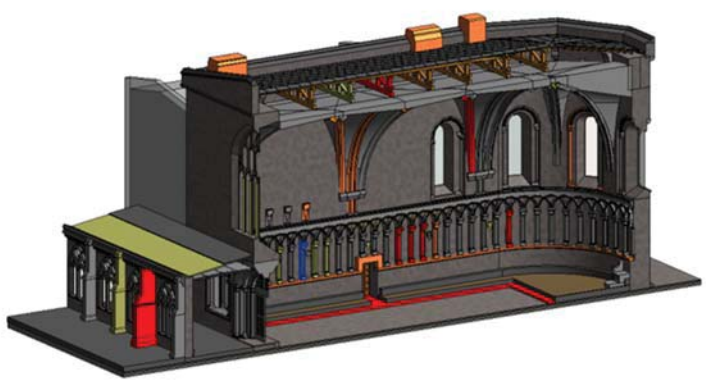

Figure 6 Condition parameter that color codes elements in the model for maintenance

- Enabled the creation of maintenance schedules directly from the BIModel (Figure 7).

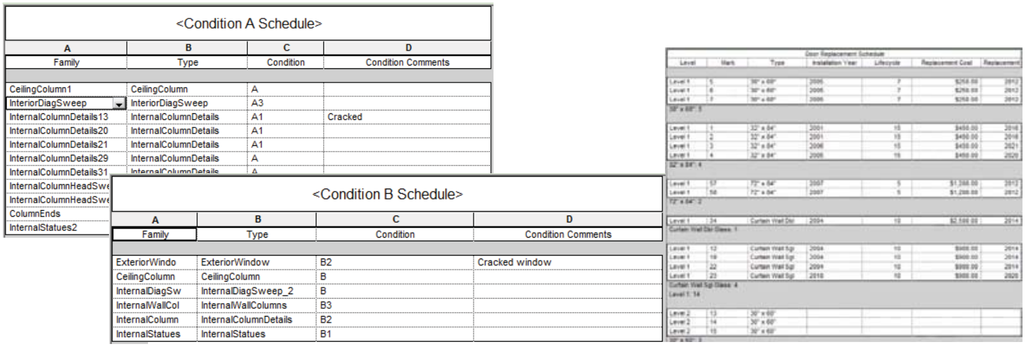

Figure 7 Maintenance Schedule created for the various elements

- Created detailed room data sheets with a log of past issues and actions.
- Provided accurate stone surveying: high resolution Point Cloud allows to take sections of the building and the survey of their condition thus, minimizing site disruptions and decreasing surveying costs.
- Enabled visual walk-through around the facility for virtual tours.
- Scaffolding simulation for refurbishment planning can be also provided when needed.
- Facilitated scenario planning and simulation (e.g. plan an exhibition inside a room).

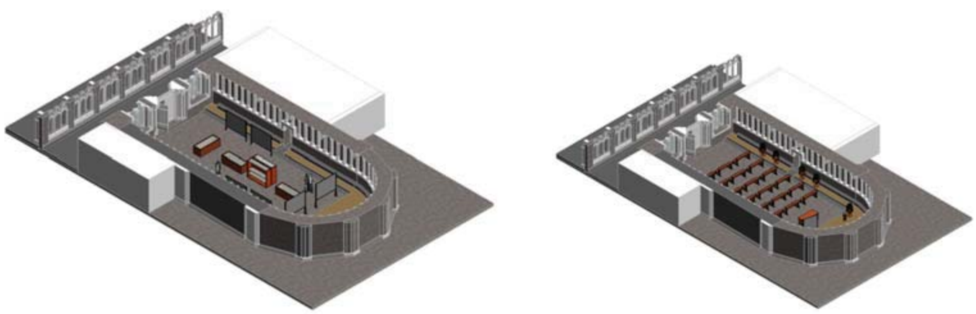

Figure 8 Different scenario simulations for planning events

- Provided remote and convenient access to information and models with the support of mobile technology (Figure 9) to e.g. explore and update the model on site and create surveys and reports.

Figure 9 Utilize the model on-site via mobile technology

Managing the building and its restoration using BIM is applicable to multiple heritage sites. Owners and facility managers can use a BIModel alongside a CAFM system to effectively plan restoration and preventive maintenance. Owners can also benefit from the production of quality

visuals for marketing purposes and to effectively communicate their requests for funding and proposals.
Following the technical presentation outlining benefits and challenges, the client and the research team discussed general issues that affect the successful adoption of BIM in heritage assets. It was concluded that heritage site are often not maintained by early adopters and innovators. Therefore, to reap the benefits of BIM in the renovation process of heritage assets, it is necessary that all relevant team members engage and support its use. This strong commitment is required to overcome the significant cultural challenge as well as the technical and procedural shift required for BIM workflows. Appropriate training and support schemes in place would facilitate the transition. To further escalate BIM adoption, it was agreed that a solid business case, based on the advantages from this pilot project, needs to be presented to demonstrate the efficiencies of improved facilities and justify the involved upfront costs.

3. Conclusion

The results demonstrated that BIM can have a significant impact in supporting and developing the existing FM processes at heritage sites. The case study illustrated how a central data-rich BIM can be created and utilized in aiding the planning and execution of the restoration and supporting the decision making of daily FM operation. A combination of the adequate hardware, software and skillset is required to achieve the whole process from laser scanning to producing a BIModel. It can be concluded that the finished model can provide historic sites with the foundation of a new digital toolkit for understanding and managing the building more efficiently and for the preservation and maintenance by future generations.

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