The complexities of managing historic buildings with BIM.

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Abstract

Purpose – The adoption of Building Information Modelling (BIM) in managing built heritage is an exciting prospect, but one that presents complexities additional to those of modern buildings. If challenges can be identified and overcome the adoption of Historic Building Information Modelling (HBIM) could offer efficiencies in how heritage buildings are managed.

Design/methodology/approach – Using Durham Cathedral as a case study, we present the workflows applied to create an Asset Information Model to improve the way this unique UNESCO world heritage site is managed and in doing so, set out the challenges and complexities in achieving a HBIM solution.

Findings – We identify the need for a better understanding of the distinct needs and context for managing historic assets, and the need for Heritage Information Requirements (HIR) that reflect this.

Originality/value – We present first-hand findings based on a unique application of BIM at Durham Cathedral, a UNESCO world heritage site. The study provides a better understanding of the challenges and drivers of HBIM adoption across the heritage sector and underlines the need for information requirements that are unique to historical buildings/assets in order to deliver a coherent and relevant HBIM approach.

Keywords: Heritage, Historic, HBIM, BIM, Facilities Management, Facility Management, BIM4FM, Durham Cathedral

Paper type: Research paper

1. Introduction

Heritage buildings have special characteristics extending beyond their physical presence. With forms, assets and systems that have evolved over centuries of modification, repair and development, they represent a universal cultural capital and a legacy for future generations. As a result, heritage buildings can offer complexities both in their form and the information they retain. How to record, organize and manage these complexities is a constant issue for the parties that manage them. However, tools, processes and approaches promoted by Building Information Modelling (BIM) could provide a solution (Maxwell, 2014). The last decade has seen an increasing use of BIM within the Architectural, Engineering and Construction (AEC) industry. Primarily focused on the design and construction processes for new builds, the co-ordination, centralizing and visualization of information has also been applied to facilities management (FM) including that of heritage buildings. This application, described as 'historic' or 'heritage' BIM (HBIM) involves "the modelling and management of historic buildings" (Dore and Murphy, 2012) and is the focus of the paper. The adoption of BIM for built heritage assets is an exciting prospect but presents complexities additional to those of other buildings. Much of the related research has focussed on the technical processes of laser scanning and model generation (López *et al.*, 2018) and lacks an approach that is "coherent and relevant whilst also taking fully into account the wide diversity of issues that affect the heritage" (Maxwell, 2014).

To address this gap in research, and from discussions with Durham Cathedral, the team was motivated to explore the challenges, complexities and opportunities of HBIM for managing historic estates. Using Durham Cathedral as a case study, we present an overview of BIM-based workflow processes and technologies applied to improve the way this UNESCO world heritage site is managed and set out the challenges and complexities in managing the estate. The research provided valuable first-hand insights into the development of an HBIM solution with functionalities to improve FM efficiencies (compared with traditional pre-BIM workflows) and in doing so, established requirements for a richer HBIM solution covering a diversity of issues and opportunities.

2. Managing heritage buildings with BIM

'BIM' can refer to both a model *per se*, or a process; i.e. that of "creating and managing information on a construction project across the project lifecycle" (NBS, 2017). The focus of interest in the current context is the potential to create an information rich intelligent Asset Information Model (BSI, 2019) to support the operation and maintenance phase of an historic building and provide "the structured repositories of information needed for making decisions during [its] lifecycle…" (Hull and Bryan, 2019). The information typically comes from both geometric and non-geometric data, with the former acting as a visual portal for embedded non-geometric data in a single information source (Volk *et al.*, 2014) that includes the planning and management of its maintenance and operation, as well as details of its systems and assets (Levitt, 2013).

Such a structured Asset Information Model (AIM) can offer advantages over traditional approaches including: increased efficiencies and effectiveness (time and resource) in archiving, monitoring, inspecting, visualising and surveying of sites and assets; increased efficiencies in data consistency; better evaluation of conditions and historical development; and more informed procurement, estimating and scheduling of interventions, particularly those that are outsourced. Accordingly, information is more easily shared and reused (Kivits and Furneaux, 2013). Potential applications as identified by Becerik-Gerber *et al.* (2012) and Volk *et al.*, (2014) include: locating building components; space management; controlling and monitoring energy; facilitating real-time data access; and retrofit/refurbishment/renovation planning and execution and emergency management. In addition, Volk *et al.* (2014) identify carbon foot-printing; indoor navigation; and life cycle assessment, while Kassem *et al.*, (2015) suggest fault reporting; scenario planning; and room finding and Edirisinghe *et al.* (2016) highlight preventive maintenance as potential applications of BIM4FM.

Despite this intrinsic synergy between BIM and FM research has revealed that their coalescence has yet to be achieved (Edirisinghe *et al.*, 2017; Hosseini *et al.*, 2018; Hull and Bryan, 2019; Pishdad-Bozorgi, 2017). Eastman *et al.* (2011) classified the barriers to implementing BIM-enabled FM as being process- or technology-related. According to Yalcinkaya and Singh (2014) process-related factors can include lack of collaboration and legal barriers (such as model ownership and responsibilities). Technical barriers include the lack of organisation readiness (Eastman *et al.*, 2011; Lijun *et al.*, 2016; Yalcinkaya and Singh, 2014) and interoperability between technologies (Becerik-Gerber *et al.*, 2012; Eastman *et al.*, 2011; Kassem *et al.*, 2015; Pärn and Edwards, 2017; Yalcinkaya and Singh, 2014). Additional challenges in providing BIM4FM solutions for existing building, include: defining data requirements, roles and responsibilities for loading data into the model; maintaining the model, and lack of real-world cases and proof of positive return on investment (Becerik-Gerber *et al.*, 2012). Furthermore, there is the need to digitise plans or undertake new surveys with technologies such as 3D laser scanning (Antonopoulou and Bryan, 2017; Rocha *et al.*, 2020) to first develop the geometrical digital model into which management and operational information can be embedded. These challenges are further amplified when applied to the heritage sector, where Pellicer and Jordan (2016) highlight the absence of familiarity with digital tools and processes within this sector and the added complexities and deformities of found in the geometries of heritage buildings. Della Torre and Pili (2020) also highlight the 'reuse of practices' and 'accustomed attitudes' associated with a lack of digital innovation within the heritage sector, stating that "academics and the industry are still looking for the most effective roadmap to a real implementation of digital techniques on this very peculiar market". Despite this, the authors concede that digital innovation within the heritage sector has the potential to answer a twofold expectation: more accurate surveys, supported by the evolution of tools and the accustomed use of point-clouds; and secondly, a more effective way of storing and retrieving information to support knowledge management and long-term care activities. This latter expectation showcases the identification of HBIM to support restoration, periodic major maintenance works and preventive conservation (Biagini *et al.*, 2016; López *et al.*, 2018; Piaia *et al.*, 2020; Tapponi *et al.*, 2015; Della Torre and Pili, 2020), representing the most critical management aspects of historic buildings. However, where application of BIM to date has focused on the technical process of surveying and modelling, "BIM as an information management process (IMP) in both the operational phase of a building's lifecycle and in the delivery of conservation repair and maintenance (CRM) and restoration projects has yet to become established in the heritage sector" (Hull and Bryan, 2019). For Della Torre and Pili (2020) "HBIM should exactly bridge these two opportunities, giving the way to opportunities not yet put into practice."

The need for digital surveying to develop models for more effective information storage and retrieval, highlights that the current lack of appropriate information provides both the need for HBIM and a barrier to its adoption. Within the current culture of heritage buildings, information (2D plans, elevations and drawings, photographs, reports, operation and maintenance manuals, etc.) can be fragmented and inconsistent. This can lead to inefficient and ineffective use of data. The operational phase requires comprehensive set of well-structured asset information (Nicał *et al.*, 2016). Non-graphical information held within an AIM for modern buildings would typically relate to the operational and maintenance information of an asset and may include: its geometrical parameters and rules, manufacture; material; cost; location and performance attributes, and related optional and maintenance manuals and reports (Eastman *et al.*, 2011). Such non-graphical information would be found within parametric objects, object that know where they belong, how they relate to other objects and what they consist of (Barazzetti, 2016). Although such information is equally relevant to heritage buildings, a heritage AIM offers the opportunity to also include historical, cultural and social information (Biagini *et al.*, 2016; Tommasi *et al.*, 2016): research material, photographs, scanned documents, significance values, conservation policies and perhaps a much more enhanced form of digitisation (Edwards, 2017) relating to the characteristics of the long and rich historic use and development of the building over its existence that are not usually considered in regular existing buildings with no specific historical value (Pellicer and Jordan, 2016). Thus, a heritage AIM has the potential to not just be valuable to the operation of complex and unique heritage assets, but to also act as a structured historical record. It offers a new approach to visualising and managing historic and operational information for heritage buildings and estates, by offering efficiency and effectiveness in the conservation, long-term management and presentation of historic built assets. The key factors are (1) the 'parametric' and 'intelligent' potential of BIM; (2) the capacity of BIM to embed non-geometric information; and (3) the accessibility and flexibility to access and utilise graphical and non-graphical data

3. Durham Cathedral

Durham Cathedral has dominated the City's landscape for almost 1000 years. Constructed from 1093 to 1133, the cathedral stands today as the "largest and finest example of Norman architecture in England" (UNESCO, 2012), and was inscribed on the World Heritage List by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1986, to recognise its architectural and historic importance. Furthermore, the cathedral is designated a Scheduled Ancient Monument and Grade 1 listed property, giving it the highest legal protection for the built environment.

Based on the typical plan of a Latin cross (Figure 1), centred on the four substantial piers of the crossing, the cathedral today has been adapted, modified and refurbished over the centuries. Throughout the adaptation, modification and refurbishment, the cathedral has been in constant use. Not only as a place of worship and pilgrimage, commemoration and culture, it has also served political and military function and in more recent times has been used as a movie and TV backdrop and been a centre piece of cultural arts and exhibition. This along with the World Heritage status has brought a new demographic of visitor, that has seen the addition of and improvement to public facilities including restaurant, toilets and retail shopping. Today the cathedral attracts approximately 700,000 visitor's pa, whilst still being used for daily services, which brings with it its own set of logistical challenges and adds to weekly running costs of £60,000 per week and the requirement of continual maintenance (Durham World Heritage, n.d.).

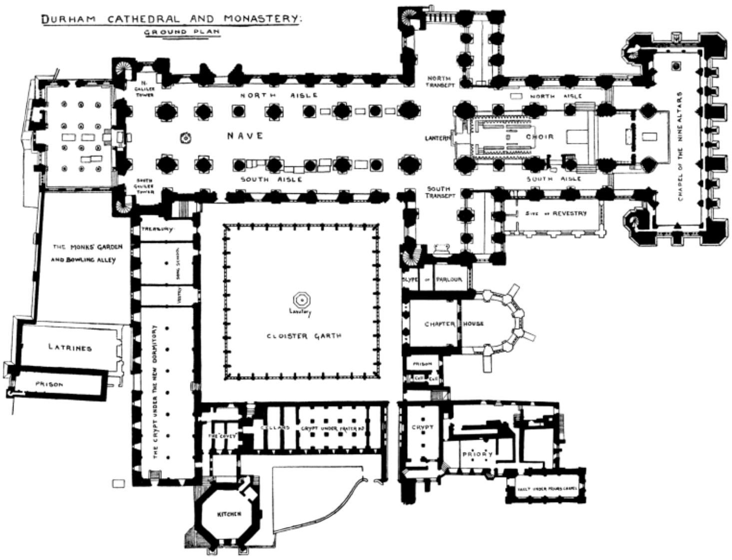

Figure 1: Durham Cathedral Plan (Bygate, 1900)

4. Methodology and rationale

The main aim of this research was to gain insight into the challenges and complexities of managing a historic estate as a prelude to developing an HBIM solution that provides functionalities that improves efficiencies compared with traditional pre-BIM workflows. As a UNESCO world heritage site and a Scheduled Ancient Monument and Grade 1 listed property, the cathedral is a complex, unique and highly protected building, with layers of history embedded in its structure, a collection of unique assets, a variation of uses by a range of different users, a constant program of maintenance and repair and a high running costs. Efficiencies need to be made to help manage and maintain the cathedral for future generations and to ensure limited budgets support the immediate and long-term running of this culturally and spiritually significant building. As such, the Cathedral provides a valuable opportunity for providing much needed insight into the potential benefits, challenges, and complexities of a HBIM solution.

The methodology adopted is shown in Figure 2. The research team first carried out initial discussions with the estates team to identify a suitable part of the cathedral for the project and to understand their challenges, drive and requirements. To create the AIM the research undertook a scan-to-BIM approach: (1) accurate documentation of the site using laser scanning; (2) registration of individual scans to create a single point-cloud; (3) optimisation and export of point-cloud to support the modelling of the AIM; (4) geometrical modelling of the AIM based on exported point-cloud; and (5) integration of non-graphical and historical information. Finally, the research team presented the resulting AIM back to the estates team to understand its effectiveness in supporting their FM needs, and the challenges and opportunities for adoption within their FM processes.

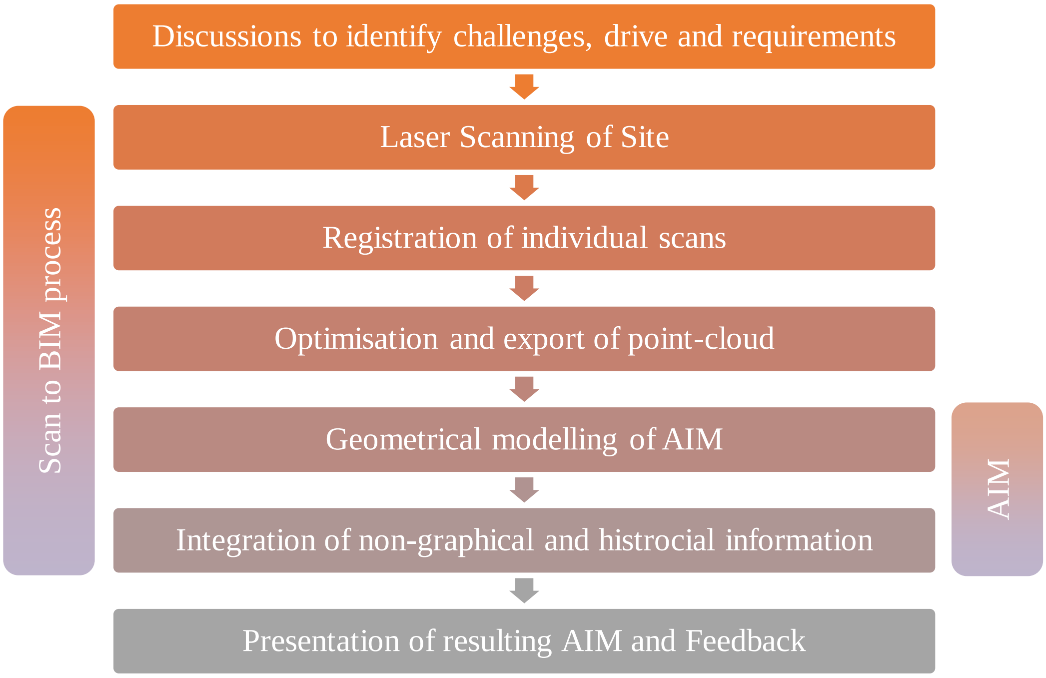

Figure 2: Research Methodology

5. A BIM solution for managing Durham Cathedral

In managing the Durham Cathedral, the FM team were hindered by the accessibility (often held offsite) of relevant and up to date drawing materials, reports, etc. and the fact that they were frequently misplaced, unorganised and inaccurate. There is no systematic way of accessing and searching the information and there is a lack of indexing of the information that currently exists. This lack of accuracy and accessibility to the drawing material and supporting information has resulted in inefficient processes and increased costs to projects, with architects and contractors having to be paid to make bespoke studies per project, potentially duplicating effort, adding to the time and cost of a project. Furthermore, due to the lack of information about the structure's build-up, other than by intrusive surveying, it was difficult to determine typical measurements (thickness and volume) that are needed for the restoration process (Tapponi *et al.*, 2015).

To investigate the potential of a HBIM solution, the Chapter House at Durham Cathedral was selected. This part of the project aimed to capture and model the historic structure to create a 3D AIM to support its improved management.

Scan to BIM

The first stage was to identify a source of base data that could be used to support the modelling process. As existing drawings were deemed inaccurate, or were inaccessible, the team opted to utilize a laser scanning approach to create an up-to-date and accurate record of the cathedral. Accurate measured surveys have long been recognised as an important part of the renovation and redesign process and have a fundamental role in BIM for existing and heritage buildings. Carbonari *et al.* (2018) highlight that 3D laser scanning is becoming the most commonly-used process to survey and collect detailed geometrical data of existing buildings in order to create as-built 3D models, a process called Scan-to-BIM (Hajian and Becerik-Gerber, 2010). Laser scanning has proved to be a vital tool in the production of surveys of existing buildings for BIM, with key advantages over traditional surveying methods. Not only is the approach faster than traditional surveys (Bu and Zhang, 2008) but it can accommodate the much higher level of detail required for 3D (Antonopoulou and Bryan, 2017).

A laser scanner emits a pulsing or continuous laser beam that bounces back to give a location (Arslan and Kalkan, 2013). The process is repeated upwards of a million points a second, as the scanner sweeps horizontally and vertically over the surrounding area. There may be a need to carry out additional scans if, for example, the area to be scanned is greater than the unit's range and/or if parts of the environment are obstructed by other elements. The result of a typical laser scanning process is a collection of individual scans or point-clouds of the area surveyed. Each individual scan can be registered with the others to create a single point-cloud.

For this pilot study the team used a FARO Focus^{3D} S 120. This survey-grade 3D terrestrial laser scanner is a phase-based panoramic-type scanner equipped with a built-in tilt sensor, barometer, and magnetic compass. The scanner has the ability to accurately capture up to 305^{O} of an environment, at a range from 0.6m – 120m, up to 976,000 points per second, with a single survey point every 3.8mm, and to an accuracy of +/- 2mm from a 25m range (FARO, 2013). Over the course of two days, the team completed 42 scans to captured external and internal features of the Chapter House. The result was a 250-million-point highly accurate point cloud of the site as well as a record of the intricate detail of the site's current condition (Figure 3). However, although very accurate and detailed, the resulting file size (8 gigabyte) was too large for efficient use within BIM authoring software. A key point for a scan to BIM process is to provide point clouds in both a file format and size that allows for efficient modelling work. The team opted to export the data as a e57 file, selected only the data required for modelling and exported at a density of 10%. The resulting file was significantly smaller in file size but retained more than enough points (10 million) to allow for efficient modelling to take place.

Figure 3: Example of captured laser scan data of Durham Cathedral

Model creation

The process of creating the BIM of the Chapter House was carried out using Revit 2015. This required the point-cloud data to first be imported into Autodesk Recap to create a compatible format, before importation into Revit. Once imported into Revit, a variety of modelling approaches were taken to "trace over" the architectural features within the point-cloud to create the final BIM (shown in Figure 4). Due to the unique nature and high architectural detail of the historic features within the Chapter House, it was not possible to use standard modelling tools (system families). Instead, the Generic Model tool was used, allowing the creation of bespoke components that were closer in detail to real architectural features, and then manually adding any object-specific parameters to it (Kelly, 2018). Even though this approach allowed for a more accurate model to be created, limitations in Revit did restrict the modelling approach, creating inaccuracies in the final model. One such error can be found in the southern wall, that was shown in the point cloud to lean out by 300mm from the vertical at the highest point of the wall. In consultation with the estates team at Durham Cathedral, it was decided to straighten this wall vertically within the BIM, to add a note to the wall highlighting the discrepancy and to provide the estates team with the point-cloud to support any measurement processes. After the geometrical model was complete, a process was undertaken to populate the model with non-geometrical information provided (reports, condition classifications, comments, etc.) and parametric data, creating a data-rich 'intelligent' AIM of the Chapter House.

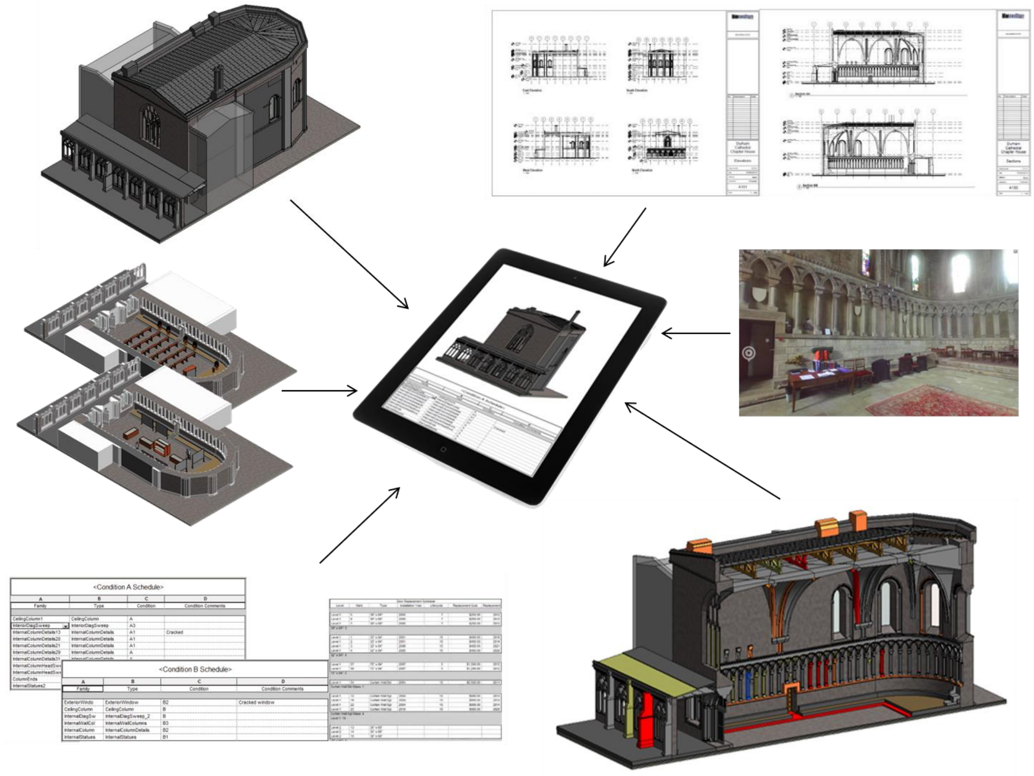

Figure 4: Resulting AIM and its features, running on a mobile device

The creation of the AIM of the Chapter House provided the estates team with an up-to-date, structured and accessible model from which traditional outputs such as elevations, sections and floor plans could be accessed, along with any attached non-geometrical information. The model also allowed the creation of condition surveys to interlink with the history of each element; maintenance schedules; accurate stone surveying; visual walkthroughs for virtual tours; scaffolding simulation for refurbishment planning; scenario planning (e.g. planning an exhibition inside a room); with field tools that utilise mobile technology being available to explore and update the model on site (Kelly, 2018) (Figure 4). One further advantage resulting from undertaking a scan-to-BIM approach related to the identification and calculation of wall and ceiling thicknesses and volumes from the modelled geometry. For the first time, the estates department were able to accurately determine the thicknesses of walls, and the volume of concrete used in the vaulted ceiling, thereby demonstrating the ability of the process to reduce the need to undertake expensive, time-consuming and potentially intrusive surveying.

6. Findings: Challenges and guidance

From undertaking the research, the team have been able to gain insight into the complexities of managing heritage buildings. It is clear that heritage buildings have unique challenges, in relation to the historical assets themselves, the accuracy and accessibility of current graphical and non-graphical information, and the processes and bureaucracy in place for managing historic buildings. However, while the use of BIM can help in these respects, new challenges emerge. The undertaken project demonstrated the potential for BIM to improve efficiencies in managing heritage buildings, by offering an accessible platform that utilizes structured digital information and 3D models to deliver greater value. The resulting AIM creates a centralised point of access for information relating to the building and its historic assets. In comparison to modern buildings, this non-geometrical information can relate not only to operational information of an asset but could also include historical information relating to the use and development of the building over its existence. In doing so, a heritage AIM has the potential to not just be valuable to the operation of complex and unique heritage assets, but to also act as a structured historical record for preserving and maintaining information for future generations. However, while the use of BIM can help in these respects, new challenges emerge.

(1) **Level of detail/accuracy.** The previous sections have examined the relationship between the architectural details of heritage buildings, the appropriateness of laser scanning in supporting data capture and BIM, and the capabilities of BIM tools to reproduce the geometrical detail. This process can be complicated depending on the complexities and detail of the historical features and assets and the needs of the client. In practice, compromises may be required between the level of geometrical accuracy (Chow *et al.*, 2019), levels of detail and the actual requirements of the model to support facilities management processes. Where accurate geometry cannot easily be created, supplementary data could be used. Within the case study presented, the team were able to provide the millimetre-accurate point cloud and a virtual tour (a bi-product of the scanning process) alongside the AIM to help with measurements and visual reviews (at time of capture).

(2) **Access to information.** On completion of the geometrical model, the next stage in creating an AIM for heritage buildings would be to embed the required non-geometrical information in a structured and useful way. However, as one of the main drivers for the initial research was the lack of accessibility and poor structure of existing information the estates team were unable to supply relevant information for the pilot study, and instead. mock data was used to demonstrate the potential capabilities of BIM for heritage. This study revealed, in the case of the cathedral, the inaccessibility and lack of structure of existing information; even at a physical level. Given the nature of such buildings it is likely that this is a situation that is typical of the heritage sector. The application of new digital technologies has been shown to improve this and offer the prospect of better structured information. However, before a program of information identification and retrieval can take place to collate the required information, further efforts are necessary to establish requirements for non-geometric information within a fully-functioning AIM, and more research is needed to establish the degree of commonality between the information requirements of heritage assets.

(3) **Technical skills.** To be able to complete a base model that can be carried forward, a combination of the adequate hardware, software and skillset is required to achieve the

whole process from laser scanning to producing an 'intelligent' AIM. Although the initial process of data capture and BIM creation can be outsourced, there may be a need for in-house capacity building, in order to utilise the model. In addition, the currency of the AIM is of paramount importance as its value decreases if it is not kept up-to-date. On delivery of the model to Durham estates, it became apparent that all relevant team members who engage and support AIM would require a level of training and initial support in to how to utilise and update the model, in order to overcome any lack of technical knowledge.

(4) **Current culture and procedures**. The delivery of an AIM for the pilot study sought to demonstrate and gain further insight into the capabilities of BIM in supporting FM processes for heritage buildings. It was clear from follow-on discussions with Durham Estates, that a further exercise was required to understand FM processes and how they can be aligned to a BIM workflow. Although the pilot study demonstrated that a wider implementation of a BIM workflow to support FM processes would have the benefit of reducing costs and increasing efficiencies and knowledge, the estates team were restricted by current processes, bureaucracy and allocated funding streams that were in place. The current processes that generated the bespoke and then inaccessible drawings would be hard to step away from as they had been in place for decades. Furthermore, although there were funding streams in place to support the running and maintenance of the cathedral, all funds for several years to come had been already been allocated. Therefore, for Durham to accelerate future BIM adoption further research was required to understand current FM processes, before a solid business case, based on the advantages from this pilot project and potential future applications, could be developed to demonstrate the efficiencies of a heritage AIM whilst justifying the improved upfront costs.

It is worth noting that many of the challenges identified for creating an AIM for heritage buildings also relate to the creation of an AIM for any existing building, (see: Becerik-Gerber *et al.* (2012); Kiviniemi & Codinhoto (2014); Volk *et al.* (2014); Kassem, Kelly, Dawood, Serginson, & Lockley (2015) and Nical & Wodyński (2016); Edirisinghe, London, Kalutara, & Aranda-mena (2017) and Pishdad-Bozorgi, Gao, Eastman, & Self (2018)), as discussed in section 2. Managing heritage buildings with BIM. However, from the review of literature, it appears that although challenges are shared, both the additional and bespoke complexities of heritage buildings, along with the culture/tradition of the sector itself and how it managers its facilities, amplify these challenges (see: Pellicer & Jordan (2016)). Furthermore, there is little research literature that addresses the significantly differing requirements of Heritage-focused BIM from new construction BIM (Arayici *et al.*, 2017).

The need for a Heritage Information Requirements (HIR)

The challenges identified can be split into two distinct areas (1) information requirements (level of detail and access to information) and (2) current culture (technical skills and current culture and procedures). The latter is a significant barrier to implementing BIM workflows into heritage buildings, and one that needs further research before recommendations can be made. However, based on the research undertaken, it is possible to make recommendations in relation to supporting the challenges that fall within the area of information requirements. For new developments, current BIM processes follow three distinct stages (1) **understanding** the client's needs and project team's capabilities; (2) the **development** of a BIM to support collaborations, communication and coordination throughout the design and construction phases, and (3) **application** within construction and/or more increasingly to support facilities management purposes.

These three stages are similarly applicable to heritage buildings; however, it is often the second and third stages (model development and application) that have attracted most attention. This study has demonstrated the technical potential for creating an AIM for heritage buildings, but in doing so has re-established the importance of the first stage (understanding) in order to drive the project and get value out of the resulting AIM. Within the application of BIM on a modern development, the project would be driven by documentations such as Organisational Information Requirements (OIR), Asset Information Requirements (AIR) and the Employers Information Requirements (EIR). These key documents set out what is required from the BIM process and any resulting AIM. However, due to the complexities and uniqueness of historical assets, along with the potential for a heritage AIM to include historical information (research material, photographs and scanned documents), these documents themselves may not deliver the supporting foundation for a HBIM process. Although further research is required to understand how current information requirements: Organisational (OIR); Employers (EIR), and asset (AIR) meet the information needs of heritage organisations, it can be proposed that for heritage buildings, there is a potential for heritage organisation to require a Heritage Information Requirements (HIR) that details specific information requirements relating to the historic assets and the unique historical information associated with heritage buildings, that can replace or work in partnership with typical information requirement documents, in order to deliver a coherent and relevant HBIM approach. The practical implications of a HIR would be to deliver value and reliance in a heritage AIM and its future use and adaption, in order to support the complex needs in managing heritage estates. By providing a better underpinning to the creation, use and future development of a heritage AIM, the proposed HIR could significantly improve the quality and relevance of the resulting AIM and in doing so provide greater efficiencies and savings in both the operational phase of a building's lifecycle and in the delivery of conservation repair and maintenance and restoration projects within heritage estate.

7. Conclusions and future research

The focus of this study has been to gain an insight into the potential application of BIM workflows in supporting facility management processes of heritage buildings. Through the application and reflection of a pilot study at Durham Cathedral the paper has provided a narrative on the creation of AIM for heritage buildings and identified the associated challenges, providing guidance for those wishing to adopt this approach. Heritage buildings are complex and unique structures. Although the research focused only one case study, the extreme nature (processes, uses, scale and size, etc.) of the cathedral has provided a valuable insight into many of the complexities that heritage buildings. It can be surmised that unlike modern buildings, for which a standard BIM methodology is more comfortably applied, heritage buildings have unique architectural details, layers of history imbedded into their structure, a requirement for constant and complex programs of maintenance and repair and have high running costs. For such buildings, it is important that efficiencies in management, maintenance and repair and use are sought to help reduce costs and preserve the historical assets for future generations. The processes and ethos promoted by BIM has been shown within this paper to have a potential to support this. Through a process of laser scanning and modelling, the team was able to deliver a working prototype of an AIM for heritage buildings. The resulting AIM successfully demonstrated the capabilities of the model to present graphical views (plans, elevations, sections, etc.) on request and embed and provide access to non-graphical data that are associated with heritage buildings and that are of use to those who manage and operate them. These non-graphical data include specifications, material properties, and reports, along with unique historical information such as research material, photographs and scanned documents. In doing so, this showcases the potential of BIM to provide an accessible, accurate and visual database for supporting facility management processes associated with heritage assets.

However, it was through this process that key challenges and areas of future research were identified. Some of the challenges identified are in common with those that relate to creating AIMs of existing buildings but are amplified and increased by the particular complexities of heritage buildings. Challenges relating to ‘levels of detail’ (LOD) and the need to carry out digital surveys due to the lack of accurate information have been discussed in the literature (e.g. in Antonopoulou and Bryan, 2017; Arayici, 2008; Chow *et al.*, 2019; Rocha *et al.*, 2020) and this research has contributed to this discussion. However, there appears to be little research that has established the need to further understand the culture of managing heritage buildings; to understand not only the technical capabilities, but the processes and formalities in place for making decisions and implementing changes that have been created by their protected status. A greater understanding of these is needed. A key challenge relates to the information requirements for heritage buildings. Due to the complexities and uniqueness of historical assets, along with the potential for a heritage AIM to include historical (historical, cultural and social) information, alongside operational information, there is a requirement on the behalf of heritage organisations to produce a template for Heritage Information Requirements (HIR) that details specific information requirements relating to the historic assets and the unique historical information associated with heritage buildings, to deliver a coherent and relevant HBIM approach. Therefore, further research is required to understand the need, potential and structure of such a HIR, in order to deliver a template that heritage organisations can implement as part of a coherent and relevant HBIM approach. The research team aims to build on the research by further developing and testing the proposed Heritage Information Requirements and associated structure, by a series of planned workshops with Historic England and estates teams managing heritage estates. These workshops will collate important empirical information as to the information requirements from this sector with the aim to gain further insight into how BIM can support the management of heritage estates.

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