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Capturing, Analysing and Interpreting the Complexities of Built Heritage in Historic Cities: Cultural Approaches and BIM Methodologies for Appropriate Conservation

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ABSTRACT

Built heritage is a key contributor to the quality of the environment in historic cities and its conservation requires a cultural approach and specific tools and methodologies to analyse and interpret its complexities. In an increasingly globalized world, it is important to conserve the character, materiality and richness of built heritage, while allowing adaptations to address current and future energy and climate issues. One of the main challenges is the perceived need for extensive retrofitting of buildings, without providing specific evidence from surveys, testing, monitoring and overall building analysis and assessments. Although Building Information Modelling (BIM) was created for designing new buildings, it is often presented as a solution to intervene in existing ones. By reviewing the relevant literature and using a case study, this paper discusses the current approaches, methods and tools concerning the use of BIM for architectural conservation and retrofitting purposes, focusing on accuracy, interoperability and integration issues. It discusses the current methodologies and the technical shortcomings in creating an accurate and reliable digital representation of existing buildings, vital to assess their condition and design the intervention, beyond the simple documentation. The findings indicate that, although BIM software is quite developed, current methodologies extensively rely on manual and labour-intensive processes, error-prone and contradicting the BIM principle of efficiency. There is also clear lack of integration of BIM and Building Performance Simulation (BPS), and thereafter a lack of comprehensive project collaboration and understanding of the building's performance. Overall, the focus is currently on the individual tools rather than on the wider cultural approach and more scientific assessments of BIM efficiency and accuracy when used in existing buildings are needed.

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1. Introduction

Historic cities are very important for people and communities' education, well-being and identity. They are complex systems with a variety of different elements, from infrastructure and traffic to parks and buildings. Historic buildings need careful attention and a cultural approach to any intervention, in order to ensure their appropriate conservation. Often, buildings are evaluated primarily for economic benefits, such as life cycle costs, investment returns or process workflow (D'Angelo *et al.,* 2022), rather than for their social, cultural, and environmental impacts. Historic England has valued in £29 billion the overall wellbeing value of heritage for people every year in England (Colwill, 2024).

The current climate crisis means that there is an urgent need, not only to conserve the buildings, but also to ensure that their energy consumption is minimised. Addressing energy issues is very much part of a conservation project, however the term 'retrofitting' is now extensively used, as it also covers non-listed existing buildings. We should however ensure that the adaptation of existing buildings to meet contemporary standards of safety, energy efficiency, and functionality, does not negatively impact in their architecture and significance. A comprehensive analysis of the built heritage, involving multiple disciplines such as history, surveying, architecture, engineering, material science, etc, is essential (Costa *et al.,* 2024).

Just to give an example of the current and global energy challenges, we can look at the situation in Europe. The building sector in the European Union (EU) is a major energy consumer and emitter, accounting for 40% of the EU's energy use and 36% of its greenhouse gas emissions, mostly from older buildings that lack energy efficiency (European Commission, 2020b). With 85% of its over 220 million units built before 2001, and largely dependent on fossil fuels, the EU promotes renovations through the Energy Performance of Buildings Directive and the Renovation Wave strategy under the European Green Deal (European Commission, 2020a). These policies aim to enhance energy efficiency by up to 22% by 2035, offering financial incentives for retrofitting inefficient buildings and ensuring protections for tenants (European Commission, 2023). The goal is a 40% emission reduction by 2030 and Net Zero by 2050, which involves substantial retrofitting of the global building stock and new constructions meeting zero-carbon standards (IEA, 2021). Unfortunately, some of the retrofitting that is being currently carried out is standardised, lacking a detailed assessment of its suitability for the particular building; this is vital in the case of historic building, as they require appropriate conservation.

The increasing use of digital modeling tools such as the Building Information Modelling (BIM) intends to improve the management of assets and data-driven processes (European Commission, 2021), as well as to facilitate the management of larger inventories of assets. BIM is a digital process that creates detailed 3D models of a building, integrating architectural, structural, and systems information. It is usually presented as a way to provide numerous benefits over traditional methods of design, management and operation of existing buildings, such as increased efficiency in archiving, monitoring, inspecting, visualizing, and surveying. This paper discusses the current approaches, methods and tools concerning the use of BIM for architectural conservation and retrofitting purposes, focusing of the key issues of accuracy and integration.

2. Methodology

Current and proposed BIM approaches and methodologies applied to existing buildings have been researched by reviewing the existing literature, and the findings have been used to define the case study. This includes the technical aspects of creating an accurate and reliable digital representation of existing buildings, vital to assess their condition and design the intervention in accordance, beyond the simple documentation of the building. The review has focused particularly on the substantial volume of publications produced over the past decade; early review papers, such as Volk *et al.* (2014), have been taken as key references for our work. The literature review revealed a predominant engineering approach to the research, rather than a wider architectural one, with a particular research focus on process engineering and algorithm development, in detriment of a wider consideration of the possible architectural intervention, which is the ultimate purpose. Commonly proposed BIM methodologies demand extensive and powerful equipment, software and human resources, unaffordable for the average practitioner. There is also a significant gap in current BIM practices, specifically concerning the lack of integrated energy assessments. As a result, it is necessary the use of other specialized tools, outside the BIM environment, for the digital analysis of a building's energy efficiency (Alhammad *et al.,* 2024).

The outcomes from the literature review have informed the selection and analysis of the case study, the Lion Chambers, which significance, condition, geometry, materiality and information datasets available, in different formats, allow for the required study. The research has been designed by exploring the feasibility of assessing existing buildings, with an emphasis on conducting a preliminary selection and classification processes. This approach aims to ensure that the most appropriate technologies are used, taking into consideration the characteristics of the building, including materiality and location, as well as the resources available. The methodologies considered have been selected based on their accessibility to architects and other professionals engaged in architectural conservation, ensuring that they are practical and widely available. The case study intends to exemplify the most appropriate methodology for capturing, analyzing and interpreting the complexities of built heritage, depending on the building characteristics, as well as to identify future research needs.

3. BIM for Documenting Built Heritage

3.1 The Challenges of Using BIM in Existing Building

BIM was created for the design and management of new buildings with the purpose of making more efficient projects by integrating in a single model all the aspects of a building, not only the geometry but also specifications, scheduling, cost, sustainability, operations and maintenance. This would allow the use of reliable and consistent data throughout the building's lifecycle. Subsequently, BIM has been applied in existing and historic buildings and named Heritage Building Information Modelling (HBIM), with the intention to focus on their conservation and management by creating detailed digital representations that preserve historical integrity (López *et al.,* 2018). However, in addition to the accurate geometry and clear specifications for managing digital building data, all BIM models need to improve process efficiency (König, 2018).

BIM is promoted for new buildings as it is assumed to increase productivity and reduce errors, allowing early resolution of potential construction problems, managing costs and time of design changes. NBS's survey found that BIM has a role as a comprehensive information management tool with possible integration with AI and digital twins (NBS, 2023). There was however also found the need for improved interoperability and standardization to enhance its construction sector impact.

The application of BIM in existing buildings presents unique challenges, particularly in complex historic buildings where the diversity of BIM platforms complicates the integration and translation of various model formats, affecting data continuity and model accuracy (Arayici *et al.,* 2018). The adaptation of BIM to existing buildings is obviously limited by the absence of original building models and the restricted interoperability of BIM tools, which may not always cater to the specific needs of architectural conservation (Alexandrou *et al.,* 2023; Costa *et al.,* 2024). Acquiring quantitative data to create BIM models from building surveys presents substantial challenges (Tejedor *et al.,* 2022). The process involves extensive digital survey data acquisition, point cloud processing, and 3D modelling. Issues with interoperability significantly obstruct widespread industry adoption (Alexandrou *et al.,* 2023).

Challenges such as different data acquisition techniques lead to less accurate simulations, and the absence of clear standards for the Level of Detail (LOD) complicates sustainability assessments, emphasizing the need for streamlined modelling processes to enhance efficiency. Challenges also persist in automating building inspections with UAVs, particularly in identifying defects on flat surfaces of rectangular buildings (Tan *et al.,* 2022). Moreover, the automatic modelling of point cloud data from laser scanning and photogrammetry into usable BIM models is slowed by the complexities and extensive time involved in the machine learning processes necessary for training datasets (Moyano *et al.,* 2022).

The path to optimizing BIM for retrofitting existing buildings involves defining clear processes and workflows. Despite proposals for BIM-based retrofit frameworks, significant hurdles remain in establishing a holistic retrofit process that encompasses accurate building assessment, software integration, and sustainability assessment. Recent advancements in Semantic BIM Enrichment process, which integrates detailed metadata about building components such as materials, historical significance, and functional characteristics, enhance BIM models for complex analyses like structural health monitoring and energy analysis (Lombardi & Rizzi, 2024).

3.2 Data Acquisition and Geometrical Model Accuracy

Traditional surveying methods are often slow and error-prone, posing significant limitations for conservation purposes. The demand for accurate 3D representations and reliable building performance simulations requires precise geometric data, material properties, and energy data, crucial for sustainable conservation (Costa *et al.,* 2024). After acquiring all necessary geometric data from the building, the post-processing stage varies significantly, depending on the data collection technology employed. Digital methods include photogrammetry and laser scanning, which captures millions of spatial data points per second to produce a dense point cloud, which is then processed and used to construct detailed BIM models. Photogrammetry involves capturing digital images of the building and using specialized software to derive accurate data for BIM creation.

The integration of advanced digital survey technologies such as laser scanning and photogrammetry within the BIM framework greatly enhances the capability to capture detailed as-built information, offering a transformative approach to the documentation and analysis of complex historic urban fabrics (López *et al.,* 2018). This integration could also facilitate a deeper understanding and more effective conservation of buildings, aligning technological advances with conservation needs. However, the lack of an automated process to convert point cloud data into a 3D model significantly complicates 3D modelling. Combining BIM and GIS tools with other software could model all the required data, in a semi-automatic way, but with the opportunity to contribute to a library which ultimately will make processes to be more automated in the future (López *et al.,* 2018).

Most of the reviewed literature presents the detailed point cloud data, captured by laser scanning technology, as necessary for achieving high accuracy in historic building documentation. Although this is true if the laser scanning is carried out in appropriate conditions allowing full visibility of all parts, in reality there are many obscured parts and/or extensive scanning campaigns are required to achieve a full definition of the existing building. In addition, there is the problem of the conversion of the resulting point cloud to a 3D BIM model, which is currently achieved using a diverse array of techniques and tools. Despite all the attempts of automated processes, the reality is that there is still need for extensive human intervention in the selection of points to create the BIM model. Thereafter, the geometrical accuracy of the final BIM model depends on the knowledge, skills and experience of the operator and his/her ability in selecting points from the point cloud and] carrying out semantic segmentation manually. This means that the selection of a knowledgeable operator is critical, and checks are needed to achieve maximum accuracy. Laser scan technology also involves expensive equipment with maintenance requirements, as well as the software and hardware necessary for its processing.

4. BIM-BPS Integration for Existing Building

Building Performance Simulation (BPS) uses BIM models to simulate and predict building performance in areas such as energy use and occupant comfort, employing computerized mathematical models based on physical laws and engineering principles (De Wilde, 2023). A subset of BPS, Building Energy Modelling (BEM), specifically focuses on forecasting the energy consumption and efficiency of building systems, aiding in design optimization and ensuring regulatory compliance. The goal of the BIM-BPS workflow is to enable the AEC industry to evaluate and select optimal software workflows for building analysis to meet performance standards (Fig. 1). The integration of BIM with BPS in the design process has seen however limited advancement.

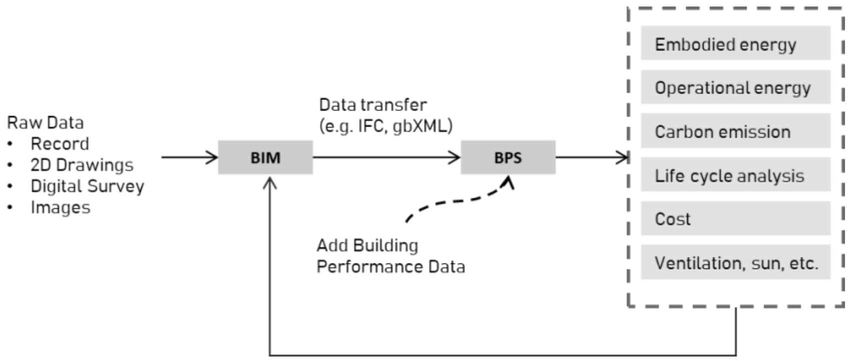


Fig. 1. General BIM-BPS framework

For appropriate conservation and retrofitting strategies, a thorough knowledge base of the building is essential, including its architecture, structure, construction, significance and future uses, as well as an understanding of user's requirements, including energy consumption. Early design decisions can be improved by simulating potential solutions based on existing conditions and energy performance criteria. Research gaps have already been identified concerning the interoperability between HBIM modelling and BEM simulation tools, the need to increase the speed of the workflow and reduce the need for data transfer, as well as the need to acquire physical data on historic buildings without damaging them (Costa *et al.,* 2024).

There are interoperability issues between BIM and BEM software due to incompatible information exchange protocols, complicating the necessary integration for energy simulation purposes. This requires the creation of a separate BEM or to augment BIM models with additional energy performance data, for example room occupancy rates and thermal bridge calculations (Khaddaj & Srour, 2016). The typical workflow involves manually transferring data from BIM into BEM for BPS analysis, a process that is time-consuming and produces inaccuracies (Yeung *et al.,* 2023). Even with a comprehensive BIM model, modifications for energy simulation rely heavily on effective data exchange, highlighting the importance of interoperability for accuracy. The challenges of interoperability represent a significant hurdle in effectively employing BPS tools during the retrofit design process, often leading to inefficient manual data entry, hindering the seamless transfer of complete building data between systems (Bonomolo *et al.,* 2021).

The process of exchanging geometrical data from BIM to BEM environments presents also many difficulties due to the excessive and complex 3D graphic data in BIM models, which often exceeds what BEM systems require. The gbXML and IFC file formats, commonly used for these exchanges, frequently fail to capture the intricacies of the original BIM models (Bastos Porsani *et al.,* 2021; Kim, 2019). Additionally, limitations in the gbXML schema restrict its ability to handle complex geometries within BPS tools, as it primarily supports basic 2D and 3D polygon shapes, which can hinder efforts to standardize across diverse building geometries (Ham & Golparvar-Fard, 2015).

Bastos Porsani *et al.* (2021) further explore the interoperability between BIM and BEM, discussing the critical need for improved integration techniques to minimize data loss and misinterpretation during the BIM to BEM transition. This study advocates for the development of standardized methods and clear guidelines to boost the reliability and efficiency of energy performance assessments in the design phase. To improve interoperability, it is often necessary to simplify models, compromising the completeness of the original data. Moreover, the need to recreate models to include essential but missing material data in energy simulations transforms the workflow into a restrictive "one-way" process. Thereafter, results from building performance simulations do not effectively influence modifications to the original BIM model, failing to enhance iterative design improvements (Patiño-Cambeiro *et al.,* 2017).

5. The Use of BIM for Architectural Conservation and Retrofitting

There is very extensive literature concerning the use of BIM for documenting historic buildings and for retrofitting existing structures, but very little about the actual use of BIM for the analysis of the condition and the actual conservation interventions, which reveals a clear research gap. To ensure a comprehensive analysis of the most relevant existing research, a systematic literature filtration and review strategy was carried out. The focus was on identifying the utilization of BIM within two interrelated domains: the methodologies for implementing BIM in existing buildings and BIM-based strategies for energy retrofitting. These areas are closely linked, as both concern to the application of BIM in the context of existing buildings, particularly with respect to the analysis of energy performance. The findings from these domains underscores the potential critical role of BIM in enhancing the energy efficiency and overall sustainability of retrofitting projects.

Table 1. Data Collection, Input Variables and Type of Analysis for BIM-BEM Association

	Building Type		Building material		Typology			Data Input						BIM			BEM				File format		Type of Analysis				References
	Existing	Historic	Masonry	Concrete	Worship place	Domestic	Non domestic	Photogrammetry	Laser Scan	Records	Manual survey	Thermal	Revit	ArchiCad	Rhinoceros	Design Builder	Open Studio	Ecotect Analysis	IES-VE	IFC	gbxml	Operational energy	Lifecylce analysis	Embodied energy	Carbon emission	
2015	X						X		X				X				X			X		X				De Angelis et al
	X					X			X			X						X			X	X				Wang & Cho
2017		X				X		X	X			X	X													Gigliarelli et al
	X						X		X			X	X			X					X	X			X	Patiño-Cambeiro et al
2018		X							X																	Bruno et al
	X			X			X			X			X										X			Marzouk et al
	X					X		X	X			X														Scherer & Katranuschkov
2019	X		X			X				X			X						X	X	X	X	X	X	X	Kim
	X						X			X			X													Bortoluzzi et al
2020		X	X				X			X		X				X							X		X	De Vita et al
		X	X			X				X			X										X		X	Feng et al
		X	X				X			X			X			X					X	X				Piselli et al
2021	X		X	X								X	X						X		X	X				Alhaidary et al
	X			X			X			X			X			X					X	X				Bughio et al
2022						X							X						X		X	X				D'Angelo et al
	X		X	X		X				X			X										X			Dauletbek & Zhou
	X					X							X										X			Motalebi et al
2023		X	X				X	X					X			X					X	X				Alexandrou et al
	X						X		X			X	X			X					X	X				Jung et al
	X						X						X	X			X			X	X		X			Yeung et al
		X			X				X	X			X						X		X	X	X			Marzouk et al
		X					X		X	X	X		X		X					X	X					Massafra et al

Table 1 summarises the findings from the literature review concerning Data Collection, Input Variables and Type of Analysis for BIM-BEM Association. They reveal how data is taken as much from existing records of the building. Recent studies highlight the strong correlation between BIM utilization and building energy management, particularly emphasizing the importance of focusing on operational energy over embodied energy due to its direct influence through retrofitting activities (Alhaidary *et al.,* 2021). They argue that, unlike embodied energy, which is established during the initial construction and less amendable, operational energy reductions can be significantly achieved through specific changes to building components. This interpretation could be challenged as the building fabric can also be transformed in a sympathetic way without damaging the building significance. However, there is a noticeable research gap about the necessary preliminary studies addressing building condition assessments before designing retrofit solutions, including thermal performance assessments using non-destructive tools, such as thermography, to better understand a building's envelope conditions (Gigliarelli *et al.,* 2017; Ham & Golparvar-Fard, 2015).

Maintaining a consistent and suitable LOD throughout each design phase is vital for enabling the necessary information exchange for energy performance analysis and leveraging BIM's full potential in fostering energy-efficient buildings (Gourlis & Kovacic, 2017). Bruno *et al.* (2018) suggested that, particularly for projects in existing buildings, the LOD should not fall below 500 to guarantee a thorough depiction of the 'as-built' condition. However, the consistent application of LOD across the various stages of BIM-based retrofitting presents challenges. Jung *et al.* (2023) proposed that an LOD of 350 is more suitable for existing buildings to narrow the discrepancy between simulation outcomes and actual energy performance. Additionally, converting point cloud data into precise digital models affects the LOD, requiring an extensively automated modelling process (Bruno *et al.,* 2018). In contrast, Brumana *et al.* (2018) recommended establishing a specific Level of Information (LOI) to foster sustainable complexity and bolster collaborative BIM practices throughout all project phases.

The diversity of methodologies is evident in the use of various software tools and data exchange formats to enhance interoperability between BIM and BEM systems (Table 1). The choice of software often depends on the specific objectives of each study, Revit and DesignBuilder being the predominantly used. Visual Programming Language tools such as Dynamo offer enhanced parameterization within Revit before exporting to Industry Foundation Classes (IFC) for BEM simulations. The complexity of transferring and converting data between these tools poses significant challenges, specially when the aim should be to produce precise and detailed BIM documentation of existing structures. There is widespread adoption of Autodesk Revit, with 18 out of 22 reviewed papers using it as BIM modelling tool for existing buildings. Within the BIM-BEM framework, the EnergyPlus simulation engine is particularly used for its applicability to projects involving HVAC systems in historic buildings, which is crucial for achieving accurate performance predictions.

Research on the integration of BIM - BPS highlights key applications in BIM modelling, data exchange and energy analysis, as well as essential output variables used in simulations. Common goals include analysing the energy performance to retrofitted existing building. BIM-BPS analysis is often used for the analysis of entire buildings (Alhaidary *et al.,* 2021; Marzouk *et al.,* 2023), while some focus on specific components targeted for retrofitting. Studies frequently reference standards, regulations, and official documents to ensure the simulation results align with the existing standards and regulatory frameworks.

Overall, the literature review reveals the need for fundamental research on the topic, the majority of published papers being review papers or the result of research done for a particular conservation project. There are some proposals for new methodologies and research development. Martinelli *et al.* (2022) proposed a HBIM workflow for the conservation and valorisation of built heritage, proposing a flexible process designed to adapt to available data and project needs. Similarly, Alexandrou *et al.* (2023) addressed the interoperability issues between HBIM and Building Energy Simulation (BES), by offering a novel data exchange method to facilitate accurate environmental analyses in historic building retrofits. Alhaidary *et al.* (2021) highlighted the need for additional manual inputs and simplifications when transitioning models from BIM to BPS tools, underscoring the importance of investigating Visual Programming Languages (VPL) to facilitate the data acquisition process from 'Scan-to-BIM' and 'BIM-to-BEM'. D'Angelo et al. (2022) introduced a BIM-based workflow that incorporates Business Process Modelling (BPM) to streamline retrofit operations across various stages from inception to demolition, enhancing decision-making through detailed lifecycle analysis and cost evaluations. There is however very little research that considers the existing building in all its architecture, materiality and cultural values, including its geometry, materials and elements, and nothing about the significance of the building and its intangible heritage.

6. Case Study: The Lion Chambers

Following from the results of the literature review, and in order to address the research gaps identified above, a case study has been selected to investigate the possible wider application of BIM in the conservation and energy retrofitting of a building. The case selected is the Lion Chambers, a Category A Listed Building in Glasgow (UK), built between 1904-1907 using the early concrete system called Hennebique. It was a mixed-use building, originally incorporating a variety of functions, including offices and artists' studios (Cusack, 1985) (Fig. 2). The building combines traditional and modern design elements, which gives further complexities to the modelling. It has however some floor plan repetition, making it more suitable for BIM modelling. The current condition of the building does not allow for full access and thereafter it was not possible to carry out a survey of a laser scan, a frequent occurrence when working with historic buildings and thereafter in need of research consideration. The source of the data was the extensive archive material about the building, including original plans, which have to be always carefully analysed against the actual building, as most of the times there are building variations during construction and indeed over the history of the buildings. Drawings of later interventions and old photographs allowed for a more comprehensive understanding of the original building and later developments so to understand the current building. We would like however to stress the fact that, for conservation interventions in historic buildings, detailed surveys and preliminary investigations are required. This study only tries to explore methodologies to adapt to various circumstances, in order to have an initial assessment of the building.

Fig. 2. Lion Chambers

In order to address the research aim to advance the utilization of BIM-based methodologies in the context of existing buildings, particularly in relation to conservation and energy efficiency, four key objectives have been set for the study of the Lion Chambers. The first objective is to acquire detailed building information to create the model, improving the accuracy and quality of BIM documentation. The second objective focuses on the input, analysis, and management of information within BIM, specifically for purposes related to conservation and retrofit design. The third objective is to explore potential methodologies for integrating BIM with energy modelling, thereby facilitating a better integration between these two processes. The fourth and final objective is to evaluate the proposed methodology and potential applications in practice.

6.1 BIM Workflow

Based on the review of existing research, a comprehensive BIM workflow has been identified, specifically designed for architectural conservation practitioners. This workflow focuses in achieving greater integration and the use of simpler tools, facilitating more efficient and effective conservation interventions. The approach aims to streamline the application of BIM in architectural conservation, ensuring that the tools used are readily available and user-friendly, thus enhancing the overall efficiency of conservation efforts. The workflow includes data acquisition, BIM modelling, quality checks, and integration with simulation tools, so that all aspects of a building project such as geometry, specifications, scheduling, cost, sustainability, operations, and maintenance are included into a single model to enhance efficiency throughout the building's lifecycle (König, 2018; López et al., 2018). The BIM methodology identified from the literature has been considered to further elaborate on the BIM-BPS process, highlighting the essential roles of documentation and information exchange. This is intended to address the challenges associated with interoperability between BIM and BEM, as well as the complexities in integrating diverse datasets (Bastos Porsani et al., 2021). The approach seeks to enhance the efficiency and accuracy of information flow, thereby improving the overall effectiveness of the BIM-BPS process in managing and analysing building performance.

Following other researchers, this study uses Autodesk Revit 2024 for architectural design and specialized simulation software, in order to support the multidisciplinary approach required in the field of architectural conservation, in which continuous data exchange among professionals is vital. This approach emphasizes the importance of integrating diverse expertise and maintaining seamless communication throughout the project lifecycle, ensuring that the conservation process is both comprehensive and effective.

The initial phase of a conservation project involves using a structured process model such as the RIBA Plan of Work and PAS 2038:2021, in order to organize the building intervention process into clearly defined stages, allowing for a precise project management. Considering that the intervention will try to achieve the conservation of the building and an energy-efficient building retrofit process, it would comprise several stages. It would begin with a thorough survey, testing, monitoring, analysis and assessment of the building, in order to define its condition, causes of decay and scope of the intervention; this would include an energy audit to understand the building's energy use and identify inefficiencies. Intervention alternatives need to be considered in an integrated way, taking in consideration conservation, energy, technical, economic, environmental, and regulatory aspects. The evaluation of these alternatives should include a clear establishment of the building significance and conservation needs, the works required to address the existing structural and material condition, energy simulation, cost estimation, and risk management. The final phase involves post-occupancy measurement and evaluation, validating the achievements, energy savings and assessing occupants' perceptions to ensure the intervention achieves an appropriate conservation while meeting both the end-user needs and performance expectations.

6.2 Data Acquisition and Creation of the BIM Model

The initial application of BIM involves data acquisition process capturing the existing state of a building and generating a pre-intervention BIM model with sufficient information (Fig. 2). This begins with the collection of building data that will be integrated into BIM software to develop the model. The methodology intends to allow that all modelling processes are adaptable to the detailed and specific needs of architectural conservation, addressing the critical need for high LOD to maintain accuracy in simulations and assessments (Bruno *et al.,* 2018; Jung *et al.,* 2023). This is crucial for managing the complexities associated with historic buildings, where maintaining data and model accuracy is often challenging due to the diversity of BIM platforms and the specific characteristics of historic buildings, as we have explained above.

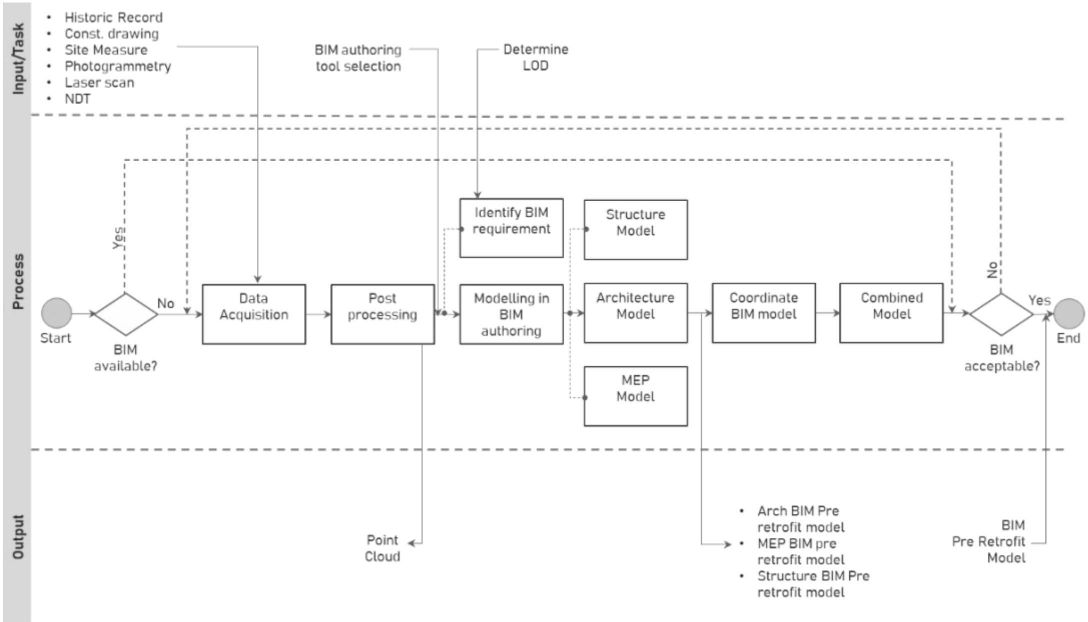


Fig. 2. The task, process flows, and output to create BIM Pre Intervention model

The BIM process shown in Fig. 3 involves utilizing analysis tools to simulate the current energy performance of the building in order to identify the most efficient retrofit scenarios to reduce its energy consumption. The initial stage involves defining the thermal zones within the building. The most common method for establishing thermal spaces in a simulation model considers three characteristics: available data, varying conditioning methods and set points, and different space functions that have various occupancy rates and internal loads (Alexandrou *et al.,* 2023). Once these spaces are established, the BIM can be exported to evaluate the existing energy performance and develop a retrofit strategy. The two primary formats for BIM file exchange are the Industry Foundation Class (IFC) and Green Building XML (gbXML). After the BIM model of the existing building has been created, the competent professional can interpret and evaluate the building's energy needs based on various energy efficiency measure factors. It is important to highlight the role of the various professional competences involved in the conservation of buildings, as BIM, like all tools and instruments, need specialist interpretation for appropriate assessment, evaluation and decision-making processes. This is particularly important in buildings of significance, so that not damage is caused by the intervention. In that sense, BIM allows for extensive testing and evaluation before the actual intervention takes place, which is a good practice in architectural conservation.

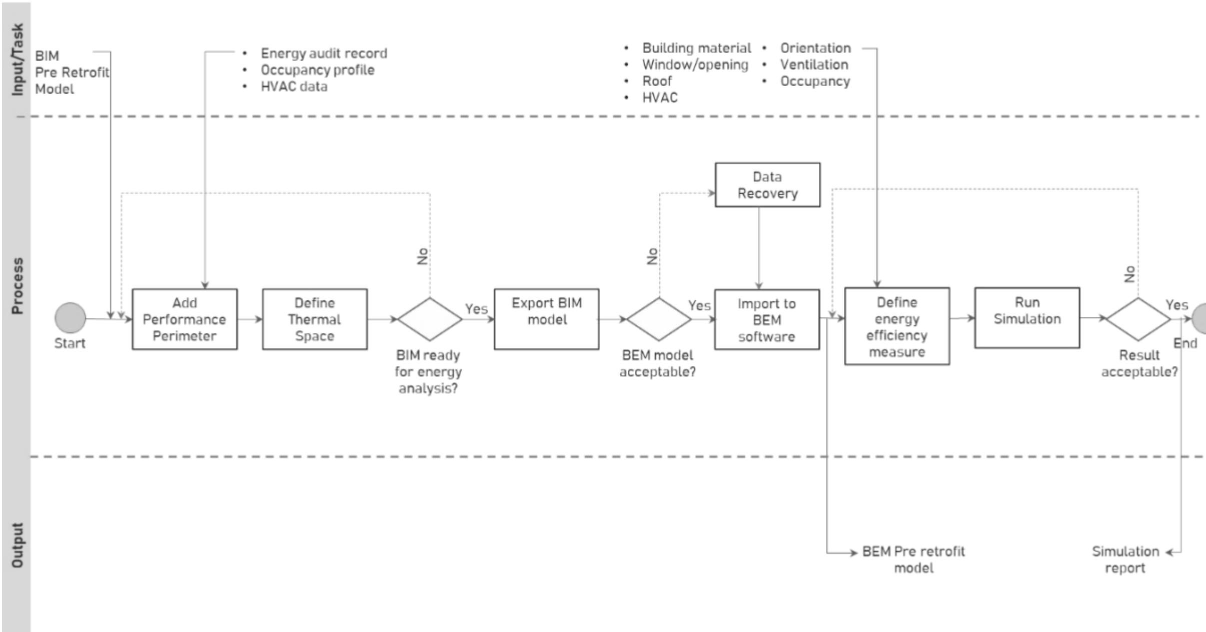


Fig. 3. The task, process flows, and output for BIM-BPS integration.

The final step involves developing retrofit options tailored to the building's characteristics, with the confidence that all the relevant building information is included in the model (Fig. 4). The process involves evaluating various retrofit design measures that may require adjustments to the building envelope, updates to ventilation systems, or both. A list of potential retrofit measures is compiled and used to update the BIM model.

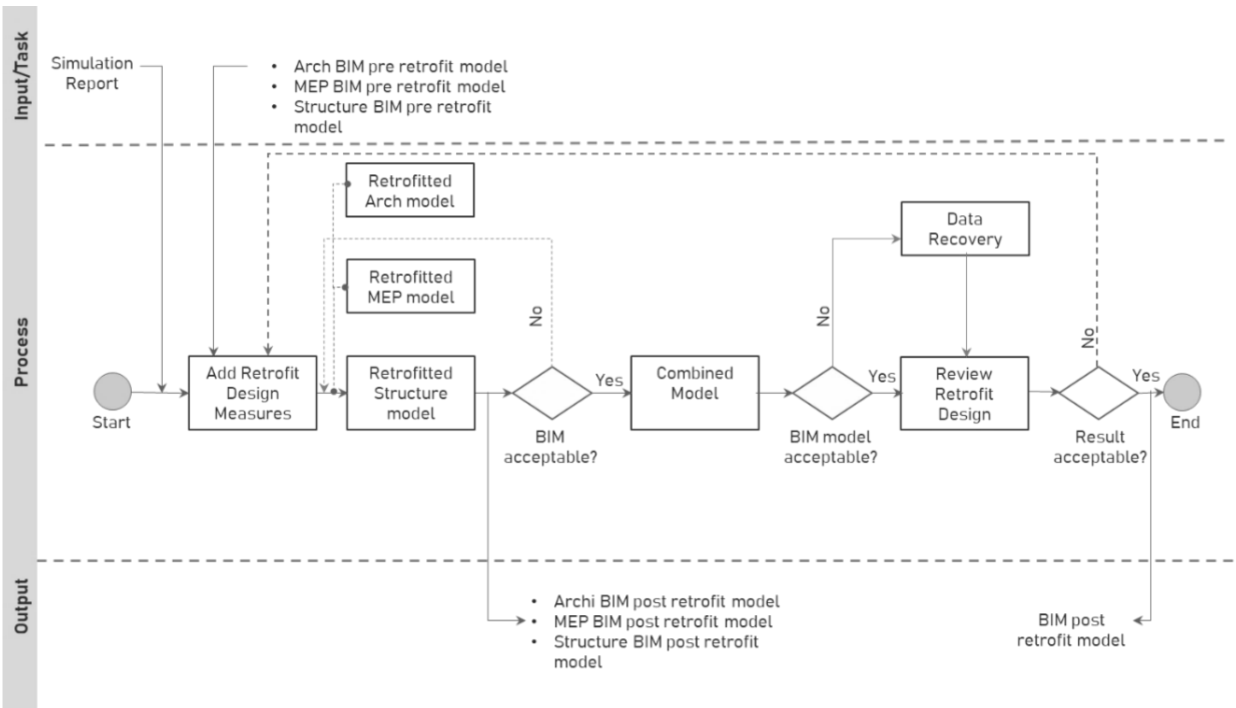


Fig. 4. The task, BIM process flows, and output for the evaluation of retrofit in a building

For architectural conservation purposes, a great emphasis has to be placed in maintaining high data accuracy and model fidelity. When 3D scans are available, each scan should be meticulously aligned and verified for errors using Autodesk Recap's registration report, followed by manual segmentation of the point cloud to simplify data handling and improve computational efficiency. The segmented data should then be imported into Autodesk Revit where the As Built FARO plug-in facilitates the creation of detailed Revit families. The final model should undergo a surface analysis to validate its accuracy against the original scans. As explained above, due to accessibility issues, it was not possible to produce 3D scans for the Lion Chambers. The project's initial phase involved collecting data from archived drawings and other documents and conducting visual inspections and direct measurements at ground floor level. In the pursue to use accessible technology, as explained above, smartphone images were used to generate 3D data (Fig. 5).

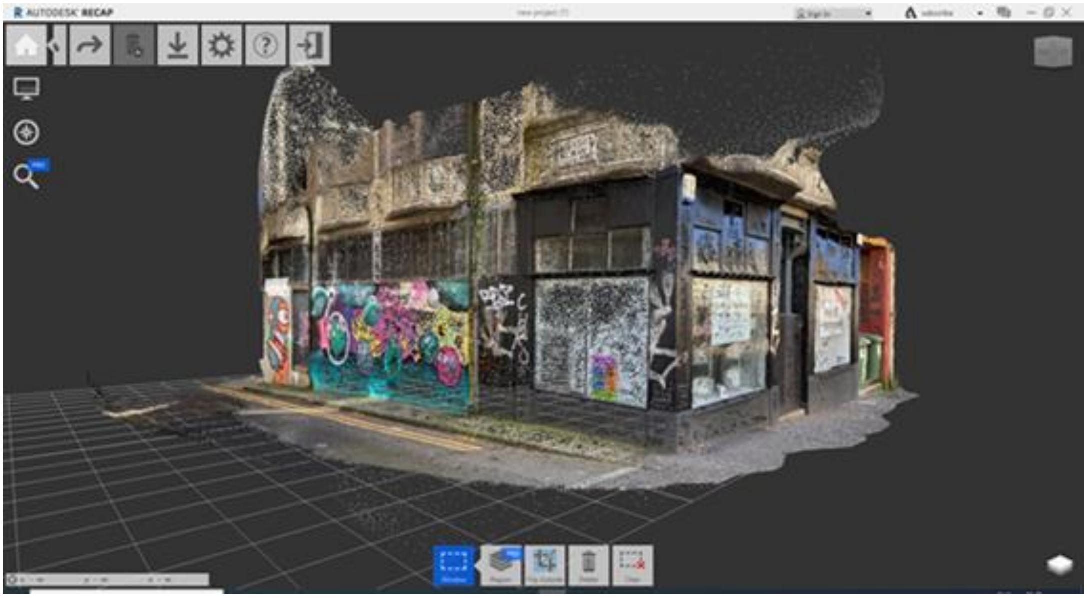
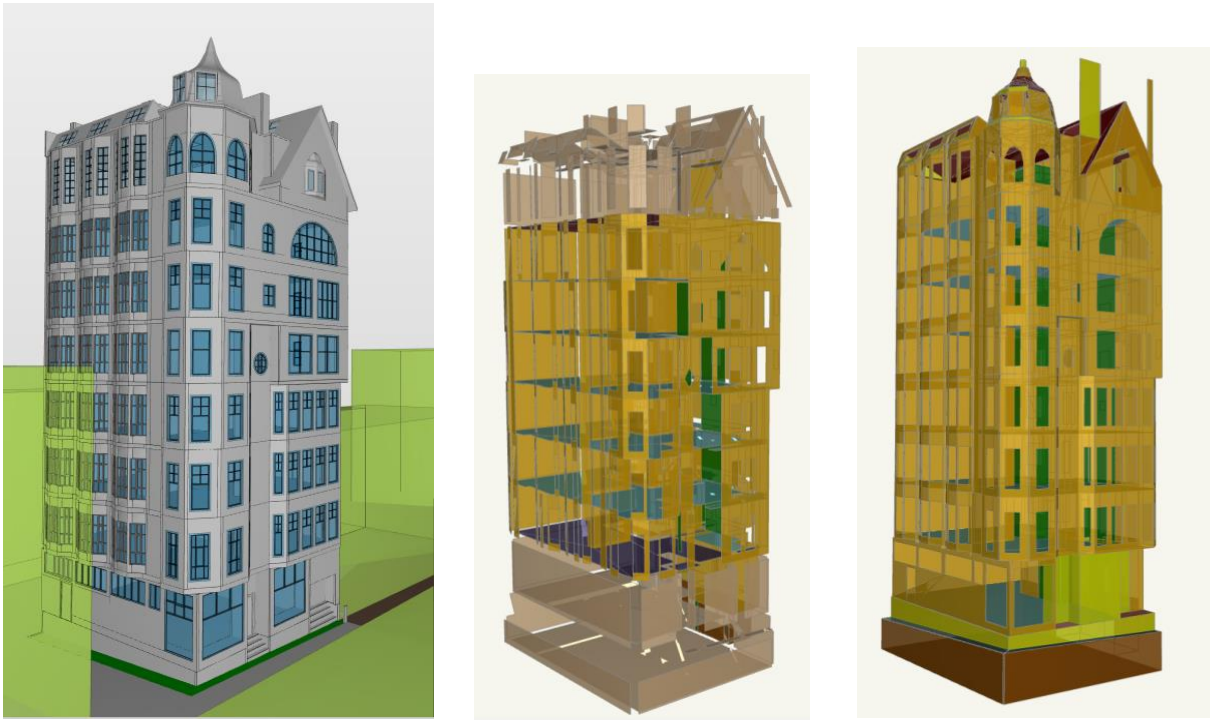


Fig. 5. Partial 3D Autodesk Recap model based on photogrammetry

6.3 Interoperability and Modelling Challenges

The first issue to note, consistent with the literature (Alexandrou *et al.,* 2023; Costa *et al.,* 2024), this case study confirms the significant challenge of interoperability within BIM platforms. As noted in recent studies (Alexandrou *et al.,* 2023; Bastos Porsani et al., 2021), transferring data across different BIM software can lead to a loss of detail and data misinterpretation. This can only be currently carried out by a manual and time-consuming operation of careful alignment and verification of scans in Autodesk Recap, ensuring high fidelity in data before transitioning to Autodesk Revit. The application of the As Built FARO plug-in in Revit facilitates the creation of detailed parametric BIM objects, which is a sophisticated approach to digitizing complex elements of historic buildings. The limitations of automatic detection features for unique shapes and details echo common issues reported in literature, where BIM tools often struggle with the irregular geometries typical of historic buildings. The case study confirms that there is always need for expert human oversight when using automated tools, as also discussed in literature (Gourlis & Kovacic, 2017; Martinelli *et al.,* 2022).

Incorporating BIM data into a BEM model requires aligning the information with the respective components, ensuring that BIM elements and the BEM database are adapted to maintain a one-to-one correspondence. There is no mandated LOD for BIM in energy simulations. We have used Autodesk Revit, starting at LOD 200, as in line with literature that stresses the importance of using robust parametric tools to handle data effectively (Bruno *et al.,* 2018). This level allows for a simplified component-based approach that considers the properties of materials such as external walls, windows, roofs, ceilings, floors, internal walls, columns, foundations, coatings, and HVAC systems. However, significant interoperability issues were encountered during the export to gbXML format where data loss during BIM to BEM transitions impedes effective energy simulation as also noted by Bastos Porsani *et al.* (2021). For this case study, we tried to ensure spatial accuracy using 'Room bounding' features in Revit, crucial for effective thermal simulation, and aligning with practices discussed in literature for enhancing BIM integration with simulation tools (Fig. 6).



(a) (b) (c)

Fig. 6. Exported Revit file into different file format: (a) IFC; (b) gbXML - exported as building element; (c) gbXML - Exported as room/surface element.

6.3.1 Quality Assurance and Energy Modelling

The use of Solibri and the Spider gbXML software (Fig. 7) for model validation underscores the critical importance of quality assurance in BIM processes, ensuring that models are accurate and meet architectural standards (Gourlis & Kovacic, 2017). This step is vital for maintaining the integrity and quality of data used in energy performance analyses and throughout the BIM process.

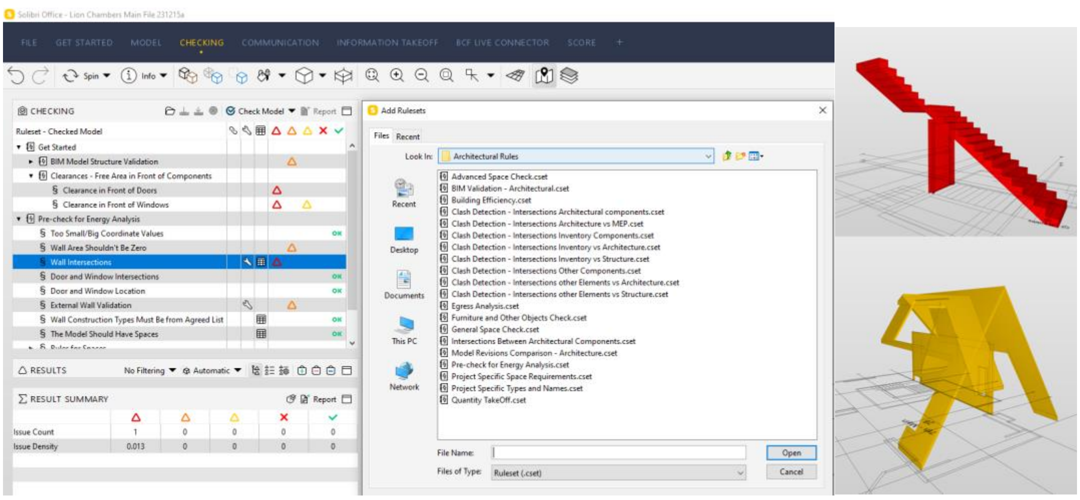
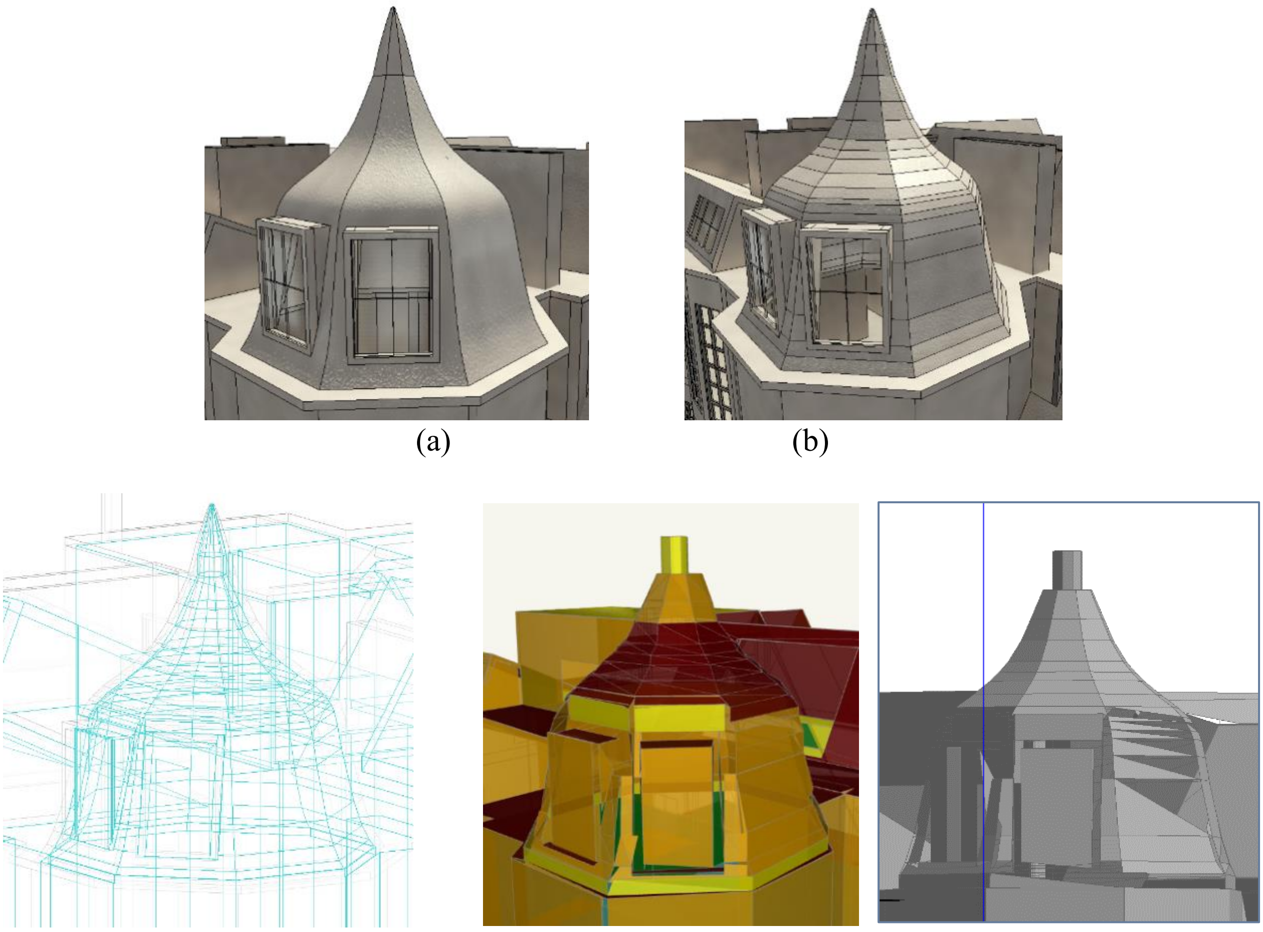


Fig. 7. Model Quality Checking and Validation using Solibri software

6.3.2 Export Challenges and Solutions

Considering the repetition present in the architecture of the Lion Chambers, Revit families were created for structural elements. Creating accurately defined analytical spaces and ensuring complete enclosures are key challenges in BIM-BPS workflows, as maintaining geometric consistency during data transfers is crucial. LOD 200 was selected, aligning with literature emphasizing the use of parametric modelling for efficient data management. This level adopts a simplified, component-focused approach that encompasses material properties, including external walls, windows, roofs, ceilings, floors, internal walls, columns, foundations, coatings, and HVAC systems. The general modelling approach emphasized parametric design principles to leverages parametric capabilities to establish constraints, levels, and relationships within the model. For example, a wall is programmed to dynamically adjust with the roof; if the roof's position changes, the wall automatically adapts accordingly.



(a) (b) (c) (d) (e)

Fig. 8. 3D Model of the turret of Lion Chambers: (a) BIM model in Revit; (b) Simplified model in Revit; (c) Analytical model created in Revit; (d) gbXML model - Exported as room/surface element; (e) BEM model in Design Builder

The case study also explored model in-place modelling using freeform elements which are crucial in historic building projects for accurately model complexities, uniqueness, pathologies, structural conditions, masonry bonding, and levels of deterioration (Brumana *et al.,* 2018). The segmentation of curved walls to facilitate successful exports, addresses one of the technical complexities involved in adapting BIM tools for buildings with unique architectural features (Alexandrou et al., 2023). This is particularly relevant for early modern reinforced concrete structures such as the Lion Chambers, presenting a variety of geometries and where standard practices might not fully capture the architectural intricacies. This produces a variety of modelling results, as it can see in Fig. 8 in the case of the turret in the corner of the building, which geometry is substantially transformed both in the gbXML model, exported as room/surface element (Fig. 8d) and the BEM model in Design Builder (Fig. 8de).

6.3.3 Future Adaptability and Parametric Modelling

The parametric modelling of building elements, allowing future modifications as more accurate data becomes available, is vital for long-term conservation and retrofitting projects (Yeung *et al.,* 2023). For example, the uniform approach to glazing, reducing multiple elements to a single parametric model, exemplifies efficiency in model management, allowing for streamlining BIM libraries to enhance process efficiency and model scalability. The thermal characteristics of opaque components like walls, floors, and roofs are automatically computed in Revit. The calculation uses the thicknesses and thermal properties of materials from the material library. This allows for the thermal properties to be assigned individually to each element. After setting the schematic types, Revit spaces and zones were designated for all building spaces which is essential data for energy simulation (Fig. 9). Revit defines spaces using the Room Bounding option available in the properties tab of all elements. Spaces boundaries were automatically traced in 2D plan views and placed within fully enclosed wall (Alexandrou *et al.,* 2023). For this project, a total of 31 analytical spaces were created. The space types were assigned based on the original building functions, such as office, exhibition space, restroom, basement, etc. The space analytical properties were assigned according to these space types because the building has been left unoccupied, and therefore, no actual data could be retrieved for this purpose. There are however issues to address, as historic buildings present a variety of geometries, construction systems and materials, some not any longer in use such as the early concrete of the Lion Chambers, and thereafter it needs to be a careful customisation, which is time consuming as many times requires also further investigation, testing and analysis.

<Analytical Spaces>

A	B	C	D	E	F	G	H	I
Composed Name	Area	Airflow per area	Area per person	Number of People	Occupancy Load	Outdoor Airflow	Space Type	Volume
02 Basement_002	5 m^2	1.60 L/(s·m^2)	20 m^2	0	0 W	0.0 L/s	Office - Enclosed	13.12 m^3
03 ST_Basement_	6 m^2	0.79 L/(s·m^2)	10 m^2	0	0 W	0.0 L/s	Stairway	19.00 m^3
01 Basement_001	148 m^2	0.00 L/(s·m^2)	33 m^2	0	0 W	0.0 L/s	Active Storage	431.84 m^3
09 1st - Exhibition	118 m^2	5.62 L/(s·m^2)	20 m^2	5.894943	777 W	49.8 L/s	Office - Open Plan	356.07 m^3
11 1st - Toilet	4 m^2	10.63 L/(s·m^2)	10 m^2	0.363681	48 W	0.0 L/s	Restrooms	10.98 m^3
12 1st - Staircase	7 m^2	9.16 L/(s·m^2)	10 m^2	0	0 W	0.0 L/s	Stairway	22.58 m^3
10 1st Lift Lobby	15 m^2	11.94 L/(s·m^2)	1 m^2	22.928272	3024 W	58.8 L/s	Lobby	47.65 m^3
13 2nd - Exhibition	118 m^2	8.16 L/(s·m^2)	2 m^2	58.827206	7758 W	244.1 L/s	Exhibit Space - Co	356.50 m^3
14 2nd Lift Lobby	15 m^2	12.07 L/(s·m^2)	1 m^2	22.779758	3004 W	58.4 L/s	Lobby	47.25 m^3
15 2nd - Staircase	11 m^2	7.87 L/(s·m^2)	10 m^2	1.089832	144 W	0.0 L/s	Stairway	33.68 m^3
16 3rd - Main	118 m^2	5.83 L/(s·m^2)	20 m^2	5.898863	778 W	49.9 L/s	Office - Open Plan	346.89 m^3
17 3rd - Lift Lobby	15 m^2	12.61 L/(s·m^2)	1 m^2	22.169745	2924 W	56.8 L/s	Lobby	44.69 m^3
18 3rd - Staircase	11 m^2	8.94 L/(s·m^2)	10 m^2	1.094564	144 W	0.0 L/s	Stairway	32.84 m^3
19 4th - Main	118 m^2	5.79 L/(s·m^2)	20 m^2	5.896559	778 W	49.9 L/s	Office - Open Plan	345.56 m^3
20 4th Lift Lobby	15 m^2	12.52 L/(s·m^2)	1 m^2	22.17102	2924 W	56.8 L/s	Lobby	44.49 m^3
21 4th - Staircase	11 m^2	9.82 L/(s·m^2)	10 m^2	1.099027	145 W	0.0 L/s	Stairway	32.88 m^3
22 5th - Main	119 m^2	5.66 L/(s·m^2)	20 m^2	5.946017	784 W	50.3 L/s	Office - Open Plan	349.64 m^3
24 5th - Lift Lobby	15 m^2	12.20 L/(s·m^2)	1 m^2	22.165956	2923 W	56.8 L/s	Lobby	44.62 m^3
23 5th - Staircase	11 m^2	9.83 L/(s·m^2)	10 m^2	1.089832	144 W	0.0 L/s	Stairway	32.69 m^3
25 6th - Main	119 m^2	5.20 L/(s·m^2)	20 m^2	5.946017	784 W	50.3 L/s	Office - Open Plan	360.35 m^3
26 6th - Lift Lobby	15 m^2	11.55 L/(s·m^2)	1 m^2	22.166396	2923 W	56.8 L/s	Lobby	46.01 m^3
27 6th - Staircase	11 m^2	9.50 L/(s·m^2)	10 m^2	1.089832	144 W	0.0 L/s	Stairway	33.54 m^3
28 7th - Main	117 m^2	10.16 L/(s·m^2)	20 m^2	5.846276	771 W	49.4 L/s	Office - Open Plan	494.30 m^3
29 7th - Lift Lobby	14 m^2	12.23 L/(s·m^2)	1 m^2	21.625298	2852 W	55.4 L/s	Lobby	51.89 m^3
30 7th - Staircase	11 m^2	11.61 L/(s·m^2)	10 m^2	1.069832	141 W	0.0 L/s	Stairway	36.88 m^3
31 Roof - Services	14 m^2	13.31 L/(s·m^2)	10 m^2	1.378509	182 W	7.5 L/s	Garage Service/Re	27.24 m^3
08 Exhibition Spac	108 m^2	6.49 L/(s·m^2)	2 m^2	54.077294	7132 W	224.4 L/s	Exhibit Space - Co	389.56 m^3
04 GF - Hallway	9 m^2	14.25 L/(s·m^2)	1 m^2	13.041602	1720 W	33.4 L/s	Lobby	31.31 m^3
05 GF Lift Lobby	9 m^2	10.73 L/(s·m^2)	1 m^2	0	0 W	0.0 L/s	Lobby	33.34 m^3
06 GF - Storage	5 m^2	0.79 L/(s·m^2)	33 m^2	0.13525	18 W	2.7 L/s	Active Storage	16.23 m^3
07 GF - Staircase	6 m^2	3.88 L/(s·m^2)	10 m^2	0.621	82 W	0.0 L/s	Stairway	22.68 m^3
31	1315 m^2							4156.31 m^3

Fig. 9. Analytical spaces and zones designated in Autodesk Revit

7. Discussion

Almost all the literature reviewed emphasized the technical complexities involved in adapting BIM for historic conservation and energy efficiency, with some underscoring the importance of precision and adaptability in digital modelling practices. There is however a lack of clarity and concerning the extensive and time-consuming manual work, essential to ensure that the digital models accurately represent the physical conditions of historic buildings, aligning also with their conservation needs. The absence of well-documented previous intervention projects complicates the ability to trace the history of repairs and maintenance within a BIM model, vital for an accurate assessment of the current characteristics and condition of the building.

Additionally, older assessment techniques and record-keeping methods typically lack the necessary precision and comprehensiveness, making the integration of historical records into BIM difficult. Although a BIM model could include all the data, we have to clearly establish the difference between documentation for historic, cultural and archiving purposes and documentation for the scope of a conservation intervention, which requires a high level of accuracy. While the development of new BIM libraries for historical elements is possible, further research is required to address the limitations of this approach. Moreover, the process of thoroughly documenting and integrating past assessments into BIM is resource-intensive, demanding considerable time and effort, which may result in incomplete documentation when resources are constrained. This contradicts the claimed efficiency of BIM and the allegedly automated processes is not such in reality. Research papers should explain more what is involved in each of the operations carried out, establishing also the time and skills involved.

Laser scanning and BIM methodologies to capture and create representations of historic element are very much promoted in literature, but the benefits are not clear at the moment; they are also unaffordable for small-medium architectural practices. Clearly its use and development, as well as the pursue of automation in the scan to BIM process are vital to develop the field and this needs to continue, but, as we have tried to explore in the case study, simpler methodologies would allow for more architectural conservation by facilitating a more affordable initial assessment of buildings, allowing for a more accurate estimation of cost and time involved in an intervention. Data acquisition integrating modern technology widely available, such as smartphones, can significantly assist the documentation, analysis and assessments of historic buildings, crucial for their conservation. It is also clear that buildings have different BIM-ability, due to geometrical and/or constructional irregularities and thereafter it has to be assessed beforehand its suitability for BIM, in order to take proportionated project decisions.

The result from the review also revealed significant efforts to incorporate BIM data into BEM. The Lion Chambers case encountered challenges related to the interoperability between different BIM tools, particularly during data exports for energy simulations and other analyses. Significant data loss occurred when exporting to the gbXML format, highlighting a common issue noted in the literature regarding the limitations of current BIM to BEM integration processes (Bastos Porsani *et al.,* 2021). The initial BIM pre-intervention model was created using Autodesk Revit and exported as IFC2×3 and gbXML files. These files underwent geometry and content analysis through automated rule checks using Solibri for IFC and Spider gbXML Viewer for gbXML. The validated model was then imported into DesignBuilder for further refinement and energy analysis. However, challenges arose during the import process, particularly in accurately representing the original model from the BIM model. Due to constraints in time and resources, the building's geometry often requires simplification to avoid misrepresentation of the original model. This simplification process is inherently subjective and depends heavily on the individual's expertise, experience, and understanding, as well as the complexity of the building. The processes require significant manual intervention to ensure the model's accuracy, due to its unique architectural features. Issues of data accuracy and interoperability challenges in historic building with automated conversions should be addressed. A difficulty in creating the workflow is to ensure that the model retained a sufficiently general LOD to not constrain the process while still adapting to various project requirements. Furthermore, the development and adoption of streamline and comprehensive workflows using open data should be prioritized by both researchers and professionals.

Additionally, discrepancies between the model schemas used by BIM software and BPS tools often result in inaccurate, incomplete, or incorrect data mappings, due to differences in object aggregation, identification, and parameterization. Addressing these challenges is crucial for improving the precision and comprehensiveness of BIM applications, particularly in conservation and retrofitting contexts that demand high levels of detail and coordination across multiple data sources. The application of semantic enrichment tools could mitigate these issues by automatically classifying BIM objects during data preparation, enhancing accuracy in component identification, but it requires extensive manual work that could be only applicable to a single building.

The reliance on manual work to address limitations of automated BIM tools is evident both in literature and in the case study. Historic buildings have not only complex geometries but also deteriorated and eroded architectural elements and materials that automated tools could not accurately model without extensive human oversight, assessment and action. The literature highlights the vital need of the involvement of experts in the different technologies and materials involved, together to well-trained technicians, so to effectively combine automated tools for architectural conservation (Gourlis & Kovacic, 2017). This includes manual segmentation of point clouds data and refinements to align automated outputs with actual conditions, vital to ensure the final BIM models' accuracy and integrity.

8. Conclusion

Although BIM software is quite developed, it is still largely based on modern materials data which requires time and effort to customise for its use in existing buildings. The results of the case study confirm the interoperability issues found in literature, particularly during data exports for energy simulations and other analyses. In addition, the research has revealed the inaccuracies built into the models by the extensive manual, error-prone and time-consuming work required in the current methodologies, in particular in the conversion of point clouds from laser scans into BIM models and in the transferring of data from BIM into BEM for BPS analysis. This is in a clear contradiction to the BIM principles of efficiency and accuracy. The lack of integration of BIM and BPS results in a lack of real comprehensive project collaboration and understanding of the building's performance.

Overall, the focus is on the individual tools rather than on a wider cultural approach and a scientific assessment of BIM efficiency and accuracy and its suitability for the specific existing building. The challenges related to geometrical inaccuracies and the lack of integration of the various datasets required in a BIM model have to be addressed more specifically in future research, as they hinder the effectiveness of BIM in accurately representing and managing existing buildings. Incorporating machine learning could refine the interpretation of scan data and improve predictive modelling of retrofit strategies. This would require a very extensive and coordinated programme to create a global library. Critical information from non-destructive testing and monitoring and other material analyses is also lacking, poorly integrated or misrepresented in the BIM models, undermining its reliability for guiding decisions on energy efficiency retrofit or other conservation and design decisions.

It is essential to explore other methodologies to identify more effective solutions and to achieve the ultimate purpose of conserving buildings in an appropriate, affordable, and sustainable way. The current simplification of models to improve interoperability compromises accuracy and completeness, missing thereafter the detail needed to intervene in an existing building. Enhancing and deploying workflows with accurate digital representation and higher interoperability could facilitate BIM implementation for existing buildings. BIM models should connect directly with databases detailing material properties and historical construction techniques, but also distinguishing between historic material to document the building and current one, representing the existing building accurately as it is today, which is the starting point for the architectural project.

The application of BIM to existing buildings has predominantly been approached from a technological point of view, often at the expense of the necessary architectural, cultural and multidisciplinary considerations. The process should begin with the clarification of the scope, objectives, and appropriate methodologies. This broader approach will better align BIM practices with the complex demands of building conservation, ensuring that the technological solutions are compatible with the cultural and ethical architectural and conservation practice, and within the legal and regulatory framework.

Interventions in existing buildings, including retrofitting works, should be based on a real need and scientific evidence, such as detailed measurements, tests and monitoring, rather than just on visual assessments and assumptions. This is imperative and required by law in the case of protected/listed buildings, so to avoid their irreversible damage. Detailed and accurate building condition assessments should be carried out before defining retrofit solutions and any BIM-based methodology for existing buildings needs to incorporate and integrate these datasets. Retrofitting buildings in an inappropriate way is not sustainable and it negatively impacts their architecture, significance and performance, leading to higher energy demands and health risks.

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