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BIM application to building energy performance visualisation and management: Challenges and potential

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A L T E R N A T I V E   N O V E L I T Y

Building information modelling (BIM) is becoming more established throughout the industry, with the intention to achieve an improvement in energy efficiency throughout the architecture, engineering and construction (AEC) industry. This paper provides an understanding of the potential for building information visualisation and management for an industry currently disparate. It demonstrates that this method is a potential means for improving the performance of BIM and building management systems (BMS) data environments. Its intention is to identify the barriers facing implementation of BIM for building designers and operators as a performance optimisation tool. The method developed links design documentation and metered building performance to identify the technological requirements for BIM and building performance connection in a real-world example. This is supplemented by interviews with designers and operators identifying associated changes and the methods challenges.

The practicality of implementing BIM as a performance management tool using conventional technologies is established, and recognises the need for more effective data management in both design and operation to support interlinking of these data-rich environments. Requirements for linking these environments are proposed in conjunction with feedback from building designers and operators, providing guidance for the production and sourcing of data to support building performance management using BIM.

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1. Introduction

The service sector accounts for 20% of UK energy consumption [1], with UK government targets for reduction of CO₂ emissions of at least 60% relative to 2006 levels by 2050 [2]. One means of achieving this goal is through projected improvement of energy efficiency throughout the architecture, engineering and construction (AEC) industry, via reduction in building energy demand. However, to achieve this, both effective design and operation must be facilitated. The recent mandate for BIM implementation on publicly funded projects in the UK is a contributor to this target [3], driving the development of efficient buildings through improved design coordination, and management of design and operations information [4].

Application of BIM to most aspects of building design and operation has been explored in depth since its emergence as an umbrella term for the processing of data describing a building. Not least of which in building performance design, simulation and optimisation, where publication trends show an exponential growth in recent years on the topic of BIM and building performance [5]. In an industry still attempting to close the recognised performance gap between predicted and measured building performance [6], methods of assisting in this process are encouraged [4], and where BIM is conveniently present as a platform on which to develop these.

Yalcinkaya and Singh [7] identified performance assessment and simulation as a target of BIM application, with energy management a growing trend within those areas. In contrast, its application to building performance management during operation is limited in favour of process optimisation, information querying and retrieval. Much emphasis is placed on the effective handover of information suitable for facilities management (FM) use [8,9] via model view definitions and export from design models [10], supported by development of open exchange formats [11]. While useful and necessary for efficient management of building and its systems [12], accessibility to information does not necessarily mean that information will be utilised, nor does it guarantee effective performance management [13].
This paper aims to identify the barriers in linking BIM with in-use building performance management. The development of a prototype method of linking BIM and monitored performance data follows a building through handover, occupation and commissioning to explore those barriers and discuss the potential requirements for data structuring and specification to support BIM as a performance management tool. The paper argues that the attribution of data within a design-based BIM environment must be such that the end-user can access and utilise it in conjunction with non-integrated data sources, and demonstrates a novel method of linking BIM and building performance data for FM use in exploring operational efficiency. Subsequent sections review existing work in this area and describe a case-study in which a BIM and performance link is created, detailing the technical, behavioural and methodological barriers in its development and application.

2. Background

The definition of BIM adopted here is as a systematic process of the management and dissemination of holistic information generated throughout building design development and operation. Several definitions of what it means are available for BIM in various contexts [14], fundamentally describing the exchange, interpretation and utilisation of meta-data surrounding a CAD model, supporting multiple functions for various stakeholders in a construction and operations process.

Reducing the gap between predicted and actual building performance is an area where much effort has been targeted. The reasons for this gap have been identified by Way and Bordass [15], who suggest frequent energy audits and continuous commissioning can optimise operational efficiency. Use of BIM as a platform on which to enable this has been explored by Dong et al. [16], who demonstrated its potential while suggesting the need for more effective data management to support it. Implementing BIM as a performance management tool has not yet been adopted beyond research, potentially a result of the numerous barriers in place to application of BIM in complex and error-prone processes; though its potential has been identified [4] suggesting further investigation of how to meet this challenge.

Lack of BIM outside design environments is representative of the slow uptake in adoption of new technologies throughout the AEC sector [17]. Disparity between the schools of thought on adopting BIM for niche purposes is demonstrated between Kiviniemi [18], who proposes the client as the driver for adoption of BIM, and Howard and Björk [19], who suggest responsibility of the designer in sharing development to drive further utilisation. Each are valid, yet both demonstrate the lack of effective implementation regardless of supply and demand, as comprehensive examples detailing the use of BIM for energy management do not yet exist.

2.1. Drivers and barriers of wider implementation

Cao et al. [20] found that use of BIM to enable effective collaboration between design disciplines is a primary driver behind its adoption, with mandates and strategies worldwide aiming to increase AEC industry productivity. A by-product of these are expected to be the creation of more efficient buildings, as a result of increased design optimisation through exploration and evaluation of design options [4]. Application of BIM for building performance management has been explored by Srinivasan et al. [21] and Göcer et al. [22], approaching implementation in different ways, yet both encountering issues of BIM integration with operational information environments. Summarising their findings and those of Codinhoto et al. [8] in the context of FM activities, the initial barriers facing effective application are:

- Limited coordination between the design and operator in defining the provision of data to support operational management;
- Information management standards in building operation falling behind those in building design;
- Focus placed on asset maintenance issues by information providers, rather than the performance related optimisation of those assets;
- A lack of real cases where BIM application is demonstrated in a replicable form; and
- The absence of detailed guidance in how BIM could be best utilised to support ongoing building performance optimisation.

The divide between research and practice for implementation BIM in “real-world” cases as noted by Codinhoto et al. [8] is indicative of the challenges facing building operators in making the best use of the tools and data now available to them. Within the realms of academic research where many variables can be controlled and accounted for, the lack of repeatability of novel applications for BIM under controlled conditions results in limited feasibility in non-research settings. Slow uptake of BIM in these areas is proof of the remaining barriers to overcome prior to effective use by the wider industry.

2.2. BIM and performance optimisation

Application of BIM to managing building performance information during both design and operation is a potential end-goal for its post-construction use [7]. Previous examples of this have been demonstrated to benefit the buildings end-user through reduction of errors, lead times and cost in design and construction [23]; however, practical application in the optimisation of building energy performance is less widespread.

2.2.1. During design

Design stage attempts to utilise information stored in a BIM environment primarily use the interoperability functions supported by modelling in a common design environment, supporting re-use of information to reduce data duplication in multiple discipline modelling tools. Cao et al. [24], demonstrate the use of BIM in this manner, prompting the development of exchange methods between BIM and energy performance simulation tools [25], and the analysis of predicted performance [26], using BIM as a platform from which to gather information for building performance design and optimisation. Subsequently, the likelihood for performance disparity also increases due to difficulty in accurate modelling of complex high-performance features, ineffective use of those optimisations [27] and inaccuracy of predictions [28].

2.2.2. During operation

BIM’s capacity for extensible meta-data attribution to modelled objects has been used as a means of storing and potentially managing asset information [29], describing the composition of the represented buildings systems [30] and operation [31]. Most examples of BIM used for managing operational energy performance are generally simulation based, monitoring to predict in-use performance and identify deviation from predictions [32–35].

The transition between design and operation is a crucial period for familiarising users with new systems and their-use, enabling more efficient building operation. Ineffective handover can increase energy consumed and occupant dissatisfaction [36], where BIM may be utilised to improve existing processes [37]. Government mandated and voluntary schemes targeting these have been implemented as part of the BIM adoption process, but further guidance is required in the application of BIM during operation in context with operational performance improvements [38].
2.3. The data management paradigm

Application of BIM as an information management platform relies on its capacity for storage and structuring of information. The modelling of objects and attribution of meta-data has been shown to enable the creation of datasets used in the management of assets post-construction [28]. The same environment federating multiple discipline designs has also been used to store maintenance information [39,31], for storage of system operation documentation [30], and demonstrating BIM as an environment through which meta-data could be accessed and exchanged [40]. Use as a data aggregation tool and its widespread adoption represents a paradigm shift from conventional document based design and operation, towards model and database style management of building data [41].

The AEC industry has only recently been required to apply methods used in database handling for the processing of large amounts of information. Such concepts applied extensively to information architectures during the mid-1990s propagating the data infrastructure underpinning the information age are now being applied to construction via big-data analysis [42,43] and BIM [44].

Haas et al. [45] demonstrates how accessing disparate information from a wide range of sources can be achieved via exchange protocols (applied via the Industry Foundation Class (IFC) schema [11]), where relational systems rely on middle-ware to support specific functionality interpreting and utilising the related information effectively. But data relation during both design[17] and operation is challenging due to the technical difficulties in linking disparate systems [46] and requirement for common standards [47].

Discordant with the availability of information describing new buildings designed using BIM, the majority of buildings for which performance improvements could be made were designed and built prior to use of 3D modelling. These lack the comprehensive models necessary to support a performance management tool [9]. Further guidance is required for BIM enhanced performance management in this area, outside the context of asset management and maintenance, simulation and fault detection.

2.3.1. Performance management efforts and standards

CIBSE [48] and ASHRAE [49] provide guidance for the efficient management of building performance, predominantly specifying operational methods, rather than the standard to which operations are measured. Several standards have been proposed to address the need for a common information standard between operational performance management and building design modelling. For example, Project Haystack [50] provides a Building Management System (BMS) data model for the structuring of information related to equipment performance management and oBIX [51], which specifies a method of communicating information generated during operation via simple web-based exchanges. However, these do not fully meet the requirements for integrated or relational information environments between a building and its representative BIM; instead, they apply modern methods of information structuring and exchange to the existing fields of BMS communications.

Additional formats for the storage of building information outside BIM environments include Green Building XML (gbXML), which is an open schema for information from BIM to be interpreted by energy modelling tools. This too could be considered the bridge between the two areas of modelling and operation with scope for time-series performance inclusion within it. However, this too faces limitations due to its ‘flat-file’ format which cannot account for the amount of data generated during operational building management [52].

The method presented here demonstrates a potential means of linking a BIM model with monitored and recorded building performance data. Care has been taken to limit reliance on proprietary software where possible to establish non-platform specific requirements for such a method. The findings here are for building designers and operators to use in determining the effective generation and handling of performance describing information in and around BIM environments, and the utilisation of this data in the ongoing performance management of the building it describes.

3. Linking BIM and operational performance

The method presented follows the latter-stages of design development, and subsequent handover and operation of a 30,500 m², 3000 person non-domestic office building completed in 2013 (Fig. 1). Developed prior to widespread BIM implementation, the information available describing the building, its constituent systems and performance were held in disparate uni-federated design models and documentation from various disciplines, representative of the majority of data describing buildings in-use currently [9]. Design specifications aimed for extensive monitoring and environmental control for energy use reduction, in conjunction with high-resolution measurement of space, system and equipment performance. Monitoring was achieved using a BMS, recording information from thousands of sensors throughout the building, storing results in a Structured Query Language (SQL) database. The choice of this building was due to accessibility of its design and operational data, and its status as an occupied building without detailed BIM documentation made it representative of many buildings for which such information is also unavailable.

Practice-led research was used to identify the barriers in-place for widespread BIM application to building performance monitoring, through development of as-built models for simulation, creation of a performance attributable and accessible BIM model and an interface between these environments and monitored performance information. The development of a simple method of linking BIM to this data used throwaway prototyping, a subset of the rapid application method for the development of software. A simple working model of the process of creating, managing and linking design and operations performance data is created quickly, to demonstrate practicality without robustness testing [53, p. 45–46], the feasibility of which is then discussed in context with feedback from producers and users of this dataset for a holistic review of BIM implementation as a performance management platform.

The tools used in the development of a prototype BIM and performance monitoring link are described in Table 1. These are typical of commonly used software platforms used during building performance design and operation, with the exception of the BMS front.
end and Python, which were the means through which data interoperability and interpretation was achieved.

3.1. Design performance information

The primary method of collecting information describing the case-study building was via document review, utilising drawings developed by the design team and supporting documentation to provide a comprehensive background to the building’s composition and intended performance. Potential for bias from selective information survival is present [60]; however, given the need for creation of a model and further investigation of the building, potentially incomplete, inaccurate and disorganised information [38] could be disregarded. With increasing information generation during design and operation an inevitable result following more widespread use of digital modelling techniques [61], the amount of information being generated using BIM requires effective management.

3.1.1. Performance prediction and attribution

Predicted building performance data was mainly generated prior to the developed design; setting the standard to which the designed building should perform for specification of systems and operating methods. The information gathered from the document review used the most recent design simulations (created using IES-VE), updated to include major changes in the buildings operational methodology and utilisation to generate a more accurate model. No comprehensive BIM models existed of the case-study building, with only partial architectural and structural models available. Accurate recreation of the entire building would have taken significant time, therefore a simplified representation of spaces and systems was chosen as a demonstrative BIM environment to which building performance data could be attributed and utilised. Space and system meta-data describing performance characteristics such as the maximum expected lighting, heating, cooling and small power loads for each space were taken from the simulated performance model and attributed to their respective spatial objects. This process used scripts written in Dynamo to interpret output from the simulation, using space names as shared attributes for coordination and transfer. Revit was used to access data within the partial models and was subsequently chosen as the platform in which to store the building design performance data, using its extensible meta-data attribution capabilities commonly employed for these means [9].

3.1.2. Performance data access and extraction

Since Codinhotol et al. [8] identified that access to data stored within BIM environments is a factor in reducing adoption in FM, accessibility has increased through development of tools interoperating between BIM authoring platforms [40]; however, a gap between the data generated during design and use remains that could be overcome using basic data management.

Dynamo was used to extract basic building geometry and performance related information from the Revit BIM environment into a JavaScript Object Notation (JSON) lightweight data-interchange format (an object-mappable file which could be queried and accessed without need for proprietary authoring software) capable of interpretation via the development language used. Utilising a non-standard format for extracting and processing data from the BIM environment distinguishes the non-platform specific barriers to wider implementation of BIM from its authoring software. Dynamo was also used to attribute predicted performance data to the design model as meta-data describing spatial and system performance (Fig. 2). The more widely used IFC format was also considered as an appropriate carrier for this information, but given the limitations in extract from Revit into this format and potential loss of data [62], the alternative was created to avoid these errors and specify exact data to be included in output of a lightweight and platform agnostic format.

3.2. Operational performance information

A relational database is the industry standard method for recording, storing and managing large databases of time-series information related to the operation of a building systems, and its performance. The existing BMS present in the case-study building utilised an SQL system. This comprised over 3000 sensors reporting continuous performance via the BMS interface into a Microsoft SQL Server 2008 back-end for storage of historic data, following industry design guidance specifying such capability [63]. This form of monitoring enables the in-situ BMS to control HVAC equipment and identify faults [64].

The amount of data recorded, while dependent on resolution, detail, data type and data recording methodology remains a limiting factor in the linking of live and historical performance between BIM and operational buildings. Gerrish et al. [52] showed that while attribution of historic performance data directly into BIM formats is possible, it is infeasible given the amount of data potentially collected, and the computational capacity required for handling these datasets for which BIM is unsuitable.

3.2.1. Performance monitoring and querying

Numerous issues were identified in the commissioning and operation of the on-site BMS prior to research application, most notably the inefficiency of data update, formatting and querying. Database management techniques are essential for handling large, frequently updated datasets; however, the method implemented in the case-study building demonstrated several key faults and barriers to extraction, interpretation and analysis:

- Redundancy in database structuring meant update transaction were inefficient, reducing system performance;
- Lack of indexing in any of the recorded logs meant querying of historical performance took far longer than necessary. Provision

| Table 1 | Software used during development of the BIM-linked performance monitoring method |
|---------|---------------------------------------------------------------------------------|
| Software | Function |
| IES-VE [54] | Modelling and simulation of building performance |
| Autodesk Revit [55] | Modelling and attribution of descriptive performance meta-data to objects |
| Autodesk Dynamo [56] | Attribution of simulated performance output to Autodesk Revit model |
| Pyth (Pandas [57], Matplotlib [58], ipywidgets [59]) | Extraction of geometry and meta-data from Autodesk Revit into a lightweight data-interchange format (JSON) |
| | Extraction of data from BMS SQL Server |
| | Cleaning of extracted data |
| | Code interlinking JSON file with query-able performance data |
of indexes to support efficient access would need to balance the memory requirements of that index, the speed of its update when monitoring thousands of meters simultaneously and the method of querying to access the indexed data [65]; however, given the often required process of extracting historical performance for meter subsets by FM this is a requirement for effective metering:

- Incorrect commissioning of the BMS resulted in numerous gaps in recorded data following system down-time; and
- Access to data was constrained by security concerns over the network access rights for the BMS.

These issues severely hindered the development of a prototype BIM and performance linking method; however, enough historical data was gathered from the BMS to provide a dataset suitable for testing and evaluation of its potential. Given access rights to the BMS either remotely or locally, live performance could also be used; however, this would require significant modification to the BMS back-end to support efficient querying of recorded information.

3.2.2. Metered data

Upon extraction of spatial and systems performance data from the BMS, preliminary review of key meter groups displayed several errors. The sources of these were identified as incorrect installation and commissioning with the BMS, inadvertent modification following FM and maintenance activities and faults occurring as part of ongoing use. Outlier detection, removal and interpolation was used to clean the raw data and provide more suitable data for analysis. Causes of erroneous collected data were identified through manual exploration of the major meter groups present in the BMS database:

- Memory limits: As a result of cumulative rather than differential metering, values were limited to those below that of the sensors local 16-bit maximum value limit (65,535), at which the metering reset to 0. Without accounting for this error, systems may be controlled incorrectly.
- Unsuitable granularity: Periodicity and detail of metering combined to reduce record interpretability. For example, energy consumption measured in MWh to 2 significant figures indicated only on/off values rather than a more accurate and granular resolution of similar data (shown in Fig. 3);
- Missing data: Gaps in records were present in all meter types. These were interpolated across where gaps are small; but were often large enough that impact on use for analysis becomes infeasible; and
- Outliers: All meter groups demonstrated periodic outliers, potentially a result of concurrent sensor update and polling, drop-out of signal [66] or malfunctioning sensors. Outlier identification and removal from the data used the winsorized mean [67, p. 150-157] of each record as a means of identifying and removing outliers.

3.3. Linking data

The limitations of the poorly set-up database from which performance data was collected were evident, and indicated a major barrier to the effective use of monitored performance data, due to poor database design and implementation. Following error removal, the cleaned data could have been reinstated in an SQL database; however, to increase performance of the prototype method an alternative Hierarchical Data Format (HDF5) format was chosen. Choice of this format over a conventional database such as SQL was ease of storage, efficiency of access to structured time-series data (using a write-once, read many times model), portability of the data recorded, speed and accessibility using the development language [68]. While likely unsuitable for implementation in the wider AEC industry, this approximates the required performance and accessibility of a building performance database interacting with data from a BIM environment.

Pandas [57] was used for all time-series performance data exploration and error removal, including extraction from the original SQL database and storage in the HDF5 format. Visualisation of historical performance was created using Matplotlib [58]. The data held within the JSON file specifying spatial and system design performance is used as the basis for indicating performance outside expected levels. The names of each space in the design model and BMS monitored zones were matched to map between individual space performance.

Visualisation of live and historic performance for each space was made possible using an interactive python environment [69] to produce a user query-able environment in which performance could be monitored Fig. 4a. Various data visualisation and analysis methods were developed using this link, including selection of monitored variable and time-span (Fig. 4b) and historic summary to indicate historic trends (Fig. 4c). A dashboard was created to indicate performance outside expected predicted levels, linking live and historic monitored performance data with predicted performance values stored within the JSON BIM proxy (Fig. 4d).

The tools developed here represent the basic elements of a BIM linked building performance management system, developed so
that the technical encumbrances in implementing such a system could be understood and evaluated in context with those providing and utilising the information generated therein. In addition to practice-led research of the technical requirements for such a system, the psychological and processual barriers inhibiting implementation currently were also investigated.

4. Designer and operator feedback

Following development and application of a basic methodology for linking design specification BIM models with monitored building performance data. Semi-structured interviews were undertaken to understand the user based issues in implementing BIM as a performance management enabling tool must be addressed.

4.1. Semi-structured interview

Semi-structured interviews were chosen as the method for gathering forthright responses and feedback to the proposed methodology, and raise points from the users perspective around their experiences and knowledge in the context of BIM application to building performance design and management. Harrell and Bradley [70], Barriball and While [71] note that data collection in this manner may be suitable for smaller study samples and provide an in-depth contextual response.
Interviewees consisted of a member from each of the building’s design, commissioning and operation teams, framed by the interviewers experiences in studying the building’s operation and management since completion. Interviewees were: a mechanical, electrical and plumbing engineer (ME) from the design team responsible for performance design and specification of conditioning plant; a commissioning engineer (CE) responsible for installation sign-off; and the building manager responsible for the building’s energy consumption and optimisation (EM). These roles were chosen due to their holistic familiarity with the building from design completion to current operation, reducing the potential for knowledge loss through changing roles. Each interview was conducted in-person at the interviewees place of work with consent given for anonymised publication of responses.

4.2. Topics of discussion

Interview responses were transcribed and categorised into themes above, enabling the grouping of topics by common areas for discussion. A method based on that proposed by Clarke and Braun [72] was adopted, generating likely themes from the topics proposed followed by further categorisation and interpretation of overarching response themes about the topics discussed below.

The same questions were asked of each interviewee, from which responses were thematically categorised in context with respondent role in producing and utilising information in BIM environments. These questions, and the themes of discussion included:

- **Provision:** How building performance information is given to the building operator;
- **Utilisation:** How that information being utilised and what commissioning activities are undertaken to meet expected performance;
- **Challenges:** The challenges that have arisen during the commissioning and operation of the building, and how these challenges change with the provision of BIM-based information; and
- **Potential:** The future of building performance management.

4.3. Interview responses

Respondent role is indicated, allowing perspective and their responsibilities in managing building performance to be attributed to response. Each theme is grouped into issues pertaining to the process, skills and technology-based issues within, indicating the barriers and opportunities for BIM application to building performance management.

4.3.1. Drivers

Economic reasons for understanding and optimising building energy performance were the primary drivers indicated by all interviewees; however, the way in which that economy was achieved differed per respondent. The CE and ME noted direct cost savings of efficient operation and energy reduction strategies, with indirect benefit from government financial incentives for low-carbon fuel sourcing. These responses suggest the requirements for greater visibility of financial benefits as a reason for adopting potentially energy saving methods.

- **EM:** “long term thinking is easily dispensed with to make short term cash savings"; and
- **EM:** “it’s ignored [until] the bills turn up higher than expected”.

4.3.2. Provision

Provision of information by designers, and its use by building operators underpins the capability of any building operating methodology. Interviewees agreed upon the current processes used to generate and utilise that information as a major barrier to applying BIM throughout design and operation. The ME and EM indicated the lack of interest in meeting design specified performance by FM, even with clear provision of that information. However, there were instances where design specification was communicated poorly, resulting in inefficient performance. Issues such as these could be addressed through more effective communication of design intent, where the EM suggests that the time-scale in which buildings are developed impacts that communication.

- **CE:** “We’ve tried to do [BIM handover] in more recent projects, but it never feels finished, there’s always just something missing. There’s so much of it done in BIM, but then it just stops and the final bits don’t get added”;
- **EM:** “Quite often I think the [maximum potential operating] values are used, which aren’t representative of normal operation, they just state the acceptable limits. I’ve seen [those] put into the log book as the setpoints to be used!”; and
- **EM:** “I think in large complex buildings, the time-scale is so significant. If it takes 4 years to design and build, technology has moved on in that time. Open standards have the potential to be adapted in that process . . . and keep pace with technology”.

The skills-requirements for those interpreting the information handed over in any format determines its potential for interpretation. Lack of skills in interpreting information in non-traditional handover formats was seen as both a challenge and an opportunity by the ME.

In conjunction with the skills of stakeholders in providing and handling information describing building performance, the technologies used were identified as a source of some of the issues facing effective communication of design intent. During performance design the ME noted that information transfer between design platforms resulted in the need to manually recreate information. Current technologies, processes and skills impinge the ability of each stakeholder in the design process to provide relevant operational information outside the format in which it is created.

- **CE:** “[the designers] struggle to give the building operators the information they need. Handing a complete model to the FM would be good, but we’ll still need to handover files because the FM might not be able to get things out of a model”;  
- **ME:** “The process we go through is something we shouldn’t give away. We need to make sure our intellectual property isn’t given away with the BIM”;  
- **CE:** “At the time it was still when design was CAD with Excel sheets. The whole idea for the building was way back in 2005, with design starting late 2008. There were quite a few things that didn’t end up in it, lots of ideas and plans, a bit of 3D stuff to improve coordination, but beyond that it was standard CAD”; and
- **EM:** “There are very few identical buildings. I think that’s a large part of the problem; a BIM for my building needs to be specific for my building, and I need to be able to access it”.

4.3.3. Utilisation

Limited use of information provided for building energy performance management was earlier identified as barrier to effective implementation of BIM as a supporting tool, but the activities undertaken by FM could be enhanced with more effective access to relevant performance data. Identifying relevant information is the first hurdle, with all interviewees responding as such.

- **ME:** “there’s too much detail there that we need to simplify”;
- **EM:** “the quality management of the building process and installation is significant. The cost of investigating and checking the problem
is often more than the energy cost, and is overlooked. It all adds up, and there are much bigger fish to fry in terms of system optimisation. We have trouble understanding what systems there actually are”.

The skills of those using the datasets created during design were seen to be lacking by the CE, who noted that reaction to performance issues were only a result of faults indicated on the BMS. Resources for scheduled and predictive maintenance do not preclude inefficient application, with the EM noting that other similar high-performance buildings showed a reduction in operational efficiency over time as a result of lack of skills for identifying performance deficiency from these resources.

4.3.4. Challenges
The lack of defined responsibility in who owns, and can act upon monitored performance data was indicated by each interviewee. Behavioural challenges remain a significant barrier to new technology and process adoption [73], demonstrated by the interviewees as reluctance to take on additional responsibilities beyond contractual obligations. A previous experience of the ME included an anecdote where upon being asked where the BMS was, the FM responded “what's that?” as it had been hidden in a cupboard while the building was being controlled manually.

- **CE:** “it depends on their appointment. Anything beyond routine maintenance just isn’t done. They’re contracted to run the building and fix what goes wrong and that’s it”; and
- **ME:** “it’s not in their contract, and if its not there they won’t do it. The client assumes that because it’s being maintained, it’s being run efficiently and optimised, but that doesn’t happen”.

Splitting the challenges in implementing BIM for use in building energy performance management into process, skill and technology-based issues, the following themes were identified:

4.3.5. Process
The complexity of building design, handover and operation processes contribute to the difficulty in applying new methods of working, and understanding how to best apply an energy management based BIM tool in this process.

- **EM:** “if we were to go forward on implementing BIM, I’d need to procure someone with the right expertise. How would I write a specification for that? Do we just ask people ‘Do you know how to do it?’, but we can’t check that”;
- **CE:** “one of the main barriers is how complicated we tend to make things. Models we make are way more complicated than how the buildings run. And that might mean the [person we hand that to] wouldn’t understand it fully and [interpret it wrongly]”; and
- **EM:** “fixing things takes time, and the more parties involved, the more time it takes. There’s a lot of bureaucracy in the whole process, and for less tangible things like energy it’s more difficult”.

4.3.6. Skill
A combination of skills-based issues were noted, where the ability to correctly utilise a BIM model significantly impacted it’s effectiveness as an information management tool. Both design and operation side interviewees stated some distrust in whether current job roles offered the correct skills to handle information in this format.

- **ME:** “[A common reference model] has been used on other projects, but one of the problems I found was that the information inside it wasn’t put in in the right way. It was there, but as it wasn’t scheduled we couldn’t get to it”;  
- **EM:** “It takes an expert to run a performance analysis, but our clients don’t have that capability, they employ a consultant to do that, but some of the tools included in [BIM authoring packages] make it seem like it’s a simple task”; and
- **ME:** “a lot of the mentions of BIM seem to be by people who think they ought to mention it, and don’t necessarily know what they mean or anyone else means when they mention it”.

4.3.7. Technology
The EM noted apprehension over the benefits of BIM, requiring greater demonstration of previous outcomes. Clarification of potential benefits for how it facilitates information management and utilisation could potentially drive implementation further than publication of these benefits alongside guidance documents:

- **EM:** “My fear is that a lot of the potential benefits of BIM are exaggerated. What would be helpful would be to have some clear definitions, standards and guidelines, you could say BIM and I could say BIM and we know we mean the same things”; and
- **EM:** “In terms of how we move forwards, how BIM could help us understand our building needs to make real and visible. The invisibility of energy is a major problem, and making it visible to occupants means we have a chance, and where I hope clever and appropriate BIM could help”.

4.3.8. Potential
The potential benefits a BIM supported method of building energy performance information management and visualisation could provide require more cohesive information management standards. The CE mentioned experiences where, with the requisite skills and input from those responsible for the delivery and use of that information, its effective use could be experienced more readily. Addressing the responsibility issue, the EM suggested that overcoming the lack of tangibility in energy performance by using an integrated model and management system could potentially bring occupants to account for their impact. However, they also stated that responsibility for new process implementation was currently ill defined in current job roles. Standards for practical interface with information environments are yet to be developed, representative of the significant changes required for integration of these capabilities in the building handover and operation processes.

- **EM:** “what you need is a target, and you can aim for that from project inception. It should be client driven; the designers must be capable of achieving that target. The contractor must then deliver to that target, and will result in a really efficient building”;  
- **EM:** “there’s a desire to contract out responsibility for being the occupant of a building, either as an organisation or an individual. We need to be more explicit about optimising, but we need relevant standards for how to do that”; and
- **ME:** “being able to use a design model to check against monitored performance would be great. If changes were made in the building, these could be checked against design specifications and flag up a compliance or performance clash”.

5. Discussion
Previous methods of using BIM for identifying performance deficiencies neglect their wider application to the variable circumstances across the construction industry. The technical and methodological challenges facing implementation of BIM in this way are discussed, using the prototype methodology described previously and interview responses to identify key barriers.
5.1. Technical challenges

Technical challenges were identified during the development of a link between BIM and monitored building performance. Additional issues were raised by the interviewees whose experiences provide a real-world perspective on challenges to consider.

5.1.1. Information availability

A balance between the specification of detail for effective building performance management, and the manageability of that information requires consideration of its purpose and the capabilities of those utilising it. If there is too little modelled data, the number of potential uses for it are reduced, and effort may be required at a later date to recreate usable information manually. If the information provided to the building operator is extensive there is greater scope for its utilisation; however, this is contingent on the format and structuring of that information if the end-user is to be able to extract from it what they require. Information overload is an evolving issue in BIM implementation [74], with additional work required in interpreting it for FM purposes. Jylhä and Suvahto [75] recognise this via poor documentation, contributing to the paradox of there being too little information available, yet what information there is to use is irretrievable amidst a mass of non-indexed files.

Management of information for further utilisation denotes a key deficiency in current BIM and FM tools. Its classification can be achieved using existing schemas; however, standards only specify the development of design information, while incorporation of operational building data into a BIM model is limited. Creation of a single method for structuring all information related to a buildings design, handover and life-cycle is an enormous undertaking, for which existing formats such as IFC may have some capacity, but holistic implementation of this is limited [52]. Instead, specific data management systems for handling the information describing a building and its performance are required, separating the large continuously changing monitored data from more static and periodically updated FM information. Managing each data type in its own environment is practical, but separation necessitates exchange mechanisms and means of access for which standardisation is not available.

Supporting the technological capacity to link a BIM model with a BMS must be the capability of the user to manage and maintain that system. Beyond the availability of a model describing a building to the FM, upkeep and maintenance of that model is unlikely to be completed; just as the drawings and records of non-digital FM documentation weren’t.

5.1.2. Information accessibility

Analogous to the availability of information, accessibility is an intrinsic part of its effective utilisation. Handover of documentation in the form in which it was authored, is yet to be adopted from designer to FM for numerous reasons [8], of which accessibility is a major limiting factor.

Non-standardised extraction and interpretation of information as demonstrated in the method presented, is representative of the challenges facing utilisation of BIM models for purposes other than design. The need for creation of a proxy format from which data could be accessed shows that while possible, the time taken and effort to extract this information would be infeasible in most building handover and operation processes. Commercial tools to access this information directly are available; however, these incur costs in purchase and user training, and the time required for integration into an FM process for which its purpose is not yet defined.

While accessibility and availability of information underpin the potential for its utilisation, its accuracy defines how well it represents the building or system it depicts. For performance management, accuracy is essential effective interpretation, and where links with existing datasets describing performance and the building must be pertinent.

5.2. Methodological challenges

Methodological challenges in energy performance management using BIM are ancillary to the technical barriers. However, these represent the major limitations placed on its use for this purpose. The methodological challenges identified by the interviewees primarily concerned the procedures in place, and the responsibilities and skills of those managing the information generated during design and operation.

5.2.1. Stakeholder capability

The capability of those responsible for the operation of a building to interact with and make sense of information stored in non-traditional formats impacts the potential for that person to improve building performance. If understanding the building is the first step in its optimisation, employing those with the skills to interpret information, and communicate that clearly to those who can make operational changes is a logical necessity.

Provision of information without transfer of the methodology in which it was generated is a subject under close review in BIM implementation. The designers who provide that information must make it accessible without losing their intellectual property, just as the users of that information must not misinterpret design intent and incorrectly operate their building.

While not strictly a capability issue, the contractual arrangements of FM was shown to preclude the optimisation of building systems and energy performance. Several interviewees indicated deficiencies in employment contracts for those responsible for building maintenance, wherein specification of duties beyond upkeep was overlooked as it was assumed optimisation was an integral part, which it was not.

5.2.2. Process effectiveness

The methods with which information is recorded and exchanged currently do not best support utilisation of BIM in procedures outside building design. Collaboration between designer and operator at handover is limited to the seasonal commissioning and exchange of basic information, building on documentation created without the needs of the end-user fully considered. Design intent is not indicated with the transferred information, leading to misinterpretation while compilation of this alongside additional documents giving context may alleviate these issues. For example, a design setpoint may indicate an maximum possible value, but could be interpreted as a target value to which the building is commissioned.

The lack of standard methods for both performance monitoring and provision of performance data containing BIM models reduce the possibility of using BIM as a performance management tool. Individually, these can be addressed using open exchange formats; but given variability in the construction industry of FM requirements, building operating methodologies and technologies, developing a new standard for such a broad spectrum is infeasible. Instead, methods of interfacing existing data infrastructures may be more suitable.

6. Conclusions

Data management during design and operation must be more carefully considered to support effective use of it for novel purposes, and the ability to use it to inform better building performance management. Without a standard form or structure, the time taken to sort and structure that data to make it usable, is too long and costly to be effectively implemented. Specification of data management systems during building operation must account for access
to that data, and provide efficient handling of potentially large datasets. The IT sector is well versed in managing such feats, but the AEC industry is behind in its application of database administration to BIM and other data collection platforms. As handover of a building to its occupant or operator is beginning to include models, efficient handover and access mechanisms must be developed to support management of the information being communicated. Recent communication protocols provide a method for achieving this, but uptake of these amongst other new technologies remain low. The reasons for this discussed previously add to the existing issues of project complexity. These include: preventing holistic implementation of new tools and processes; project rather than organisation orientation reducing the capacity for ideas to be shared between projects with changing members; and disparity between the client and developer whose contrasting objectives must balance the clients demands to the scope and scale of the developers fee.

Against the background of BIM as a standard working process, the mindset of designers and operators must change, and adapt to the impacts new technology is having on their roles. During design, FM and building owners must give guidance for their expectations of information delivery, while designers must have the skills to deliver these requirements. Moving beyond simple handover of models and files, the responsibility for the upkeep of these must also be defined, without which dependant systems and understanding of how the building operates become ineffective.

Widespread application of BIM for purposes outside design development is unlikely to happen without corresponding and reliable standards for information management, in the areas to which it’s applied. Addressing the barriers identified here would simplify this process, and enable more effective utilisation of design and operational data in ongoing performance management. The question remains: How can information describing a buildings performance be standardised in such a way that would enable the automated application of tools to give accurate representation of where energy is being used? And how could this be supported in context with the common data environment using BIM?

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