Exploring the Effectiveness of BIM for Energy Performance Management of Non-Domestic Buildings

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EXPLORING THE EFFECTIVENESS OF BIM FOR ENERGY PERFORMANCE MANAGEMENT OF NON-DOMESTIC BUILDINGS

By Tristan Gerrish

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Abstract

Following several years of research and development around the subject of BIM, its impact on the design and handover of buildings is now becoming visible across the construction industry. Changes in design procedures and information management methods indicate the potential for greater utilisation of a Common Data Environment in areas other than design. To identify how these changes are influencing the engineering design process, and adapt this process to the needs and requirements of building performance management requires consideration of multiple factors, relating mainly to the stakeholders and processes employed in these procedures.

This thesis is the culmination of a four year Engineering Doctorate exploring how BIM could be used to support non-domestic building energy performance management. It begins with an introduction to the research aim and objectives, then presents a thorough review of the subject area and the methodologies employed for the research. Research is split between eight sequential tasks using literature review, interviews, data analysis and case-study application from which findings, conclusions and key recommendations are made.

Findings demonstrate disparity between different information environments and provide insight into the necessary steps to enable connection between BIM and monitored building energy performance information. They highlight the following factors essential to providing an information environment suitable for BIM applied performance management:

- Skills in handling information and the interface between various environments;
- Technology capable of producing structured and accurate information, supporting efficient access for interconnection with other environments; and
- Processes that define the standards to which information is classified, stored and modified, with responsibility for its creation and modification made clear throughout the building life-cycle.

A prototype method for the linking of BIM and monitored building energy performance data is demonstrated for a case-study building, encountering many of the technical barriers preventing replication on other projects. Methodological challenges are identified using review of existing building design and operation procedures.

In conclusion the research found that BIM is still in its infancy, and while efforts are being made to apply it in novel ways to support efficient operation, several challenges remain. Opportunities for building energy performance improvement may be visualised using the modelling environment BIM provides, and the ability to interface with descriptive performance data suggests the future potential for BIM utilisation post-handover.

Key words

Building Information Modelling (BIM), Energy Performance, Performance Monitoring, In-Use, Post-Occupancy

Preface

The research presented within this thesis was conducted to fulfil the requirements of an Engineering Doctorate (EngD) at the Centre for Innovative and Collaborative Construction Engineering (CICE), Loughborough University. The EngD programme is described as a, 'radical alternative to the traditional PhD, better suited to the needs of the industry'[*] the main essence being 'to produce doctoral graduates who can drive innovation in the construction engineering industry with the highest level of technical, managerial and business competence'.

The EngD is examined on the basis of a Thesis containing at least three (but not more than five) research publications and/or technical reports. Presented within this thesis are journal papers and conference papers authored by the candidate. Each paper is referenced by the section (Appendix A – Appendix E) where it can be located.

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[*]Extract from CICE website (www.lboro.ac.uk/research/cice/).

Acronyms

2D	2-dimensional geometry
3D	3-dimensional geometry
4D	Time
5D	Cost
6D	Life-cycle and Facilities Management
AEC	Architecture, Engineering and Construction
AIM	Asset Information Modelling
API	Application Programming Interface
BAS	Building Automation System
BCVTB	Building Controls Virtual Test Bed
BEM	Building Energy Modelling
BEM	Building Energy Management
BEP	BIM Execution Plan
BHoM	BuroHappold Object Model
BIM	Building Information Modelling
BMS	Building Management System
BREEAM	Building Research Establishment Environmental Assessment Method
BSON	Binary JavaScript Object Notation
CAD	Computer Aided Design
CC	Continuous Commissioning
CDE	Common Data Environment
CHP	Combined Heat and Power
COBie	Construction Operations Building information exchange
CSV	Comma-Separated Values
EIR	Employer's Information Requirements
EngD	Engineering Doctorate
EPBD	Energy Performance of Buildings Directive
EPM	Energy Performance Modelling
EU	European Union

FCU	Fan Coil Unit
FDD	Fault Detection and Diagnosis
FM	Facilities Management
gbXML	Green Building Extensible Mark-up Language
HDF5	Heirarchical Data Format
HVAC	Heating, Ventilation and Air-Conditioning
HVAC&R	Heating, Ventilation, Air-Conditioning and Refrigeration
IAI	International Alliance for Interoperability
IDF	Input Data File
IES-VE	Integrated Environmental Solutions – Virtual Environment
IFC	Industry Foundation Class
IoT	Internet of Things
IPD	Integrated Porject Delivery
ISO	International Standards Organization
JSON	JavaScript Object Notation
KM	Knowledge Management
LEED	Leadership in Energy and Environmental Design
LOD	Level of Development
MEP	Mechanical, Electrical and Plumbing
MVD	Model View Definition
nD	n-Dimensional
NIST	National Institute of Standards and Technology
O&M	Operations and Maintenance
oBIX	Open Building Information Xchange
PDT	Product Data Template
PIM	Project Information Model
POE	Post-Occupancy Evaluation
RDS	Room Data Sheet
RE	Research Engineer
SPie	Specifiers' Properties information exchange
SQL	Structured Query Language
STEP	Standard for the Exchange of Product Model Data
VAV	Variable Air Volume

Executive summary

Background

Adoption of Building Information Modelling (BIM) as a method for the management of building design information is becoming standard practice across the Architecture, Engineering and Construction (AEC) industry. Application of this method to areas outside design development, and use of BIM data for building performance optimisation is gaining traction as its impact is being felt throughout the building life-cycle. Optimisation of building energy performance can be a complex activity, given the number of factors contributing towards holistic building performance. In the context of this research, exploration of these is undertaken, with the primary objective being to understand how BIM could be applied to operational building energy performance management.

Research aim and objectives

The aim of this research was to investigate how BIM could be used for evaluation of a building's energy performance, and its effectiveness as a tool or platform in which to support performance management. The objectives listed for the development and delivery of this are detailed in Section 1.5 and can be summarised as:

– Review energy performance modelling and monitoring tools/processes in a BIM context;
– Devise a method to capture and manage operational building performance data, in a BIM environment;
– Develop and implement a pilot study using the input from the previous objectives to demonstrate the use of BIM for managing building energy performance data; and
– Synthesise the work to make recommendations for effective use of BIM for interpretation by Facilities Management (FM), and its application to managing building energy performance.

Methodology

Research was split between sequential tasks, each contributing towards a thorough understanding of the subject matter. To define further objectives and tailor research to benefit the industry sponsor, an investigation of the organisations BIM capabilities, implementation strategy and Knowledge Management (KM) methods was completed,

detailed in Section 4.2 and Appendix A (Gerrish et al., 2014). This suggested the need for a method of sharing information between building design stakeholders more effectively, instigated by those both provide and requiring that information, particularly for information concerning building performance design. Modifying existing design frameworks to suit this need is explored in Section 4.3 and published in Appendix B (Gerrish et al., 2016c).

An existing building was used as a case-study for research development and application. Existing models described this building as it was during the industry sponsor's involvement in its design; however, due to changes in design after this involvement inaccuracy resulted in the need for recreation of the as-built building. Details of the processes used to create these models is given in Section 4.4. Exploration of the potential storage of building performance information during operation indicated the steps required to link BIM and building energy performance data. Specific methods and description of this is presented in Appendix C (Gerrish et al., 2015). These findings prompted the exploration of alternative methods of attributing building performance data to existing BIM models, outside the existing formats currently available (Section 4.5). During investigation of the case-study building's performance, several issues were identified including errors in Building Management System (BMS) implementation and recording accuracy issues requiring resolution. These problems were partially addressed in Section 4.6 with the development of Python-based error handling and analysis routines, contributing to a novel performance behaviour comparison method, described in Appendix D (Gerrish et al., 2016b).

Connecting monitored and predicted building energy performance data from the BIM and BMS using Python into a series of visualisation and analysis tools demonstrated the potential for BIM application to building performance management, while identifying the current challenges in achieving this connection. The processes undertaken are detailed in Section 4.7, with evaluation of the human and process-based challenges explored using in-depth interviews with building design and operation stakeholders in Section 4.8. These were compiled in Appendix E (Gerrish et al., 2017b).

Summary of results

Major findings from the research undertaken are discussed in Chapter 5, and include:

– The effectiveness of BIM as a technology relies on the capability of the tools handling building information. The effectiveness of BIM as a process is determined by the methods used, and the abilities of those working with technology to utilise it effectively;

– Standards for information management outside design development do not yet support the application of BIM, resulting in the need for case-specific methodologies;

– Procedural changes in the development, handover and utilisation of performance information are required to define who is responsible for the maintenance of that information;

– Use of BIM in building energy performance management relies on too many factors for effective widespread application. Until holistic life-cycle building performance is considered an integral part of a modelled environment, challenges in implementation reduce potential for its use in that way; and

– The engineer and building operator's archetypal skill-set must change to account for

the changing model of building information development and utilisation. Data is becoming the new medium of exchange, and without skills in handling this effectively, the capacity to provide value through its use is reduced.

Conclusion

The research demonstrated that it is possible to use BIM as a platform for linking design and monitored building performance information, interfacing these to visualise the performance of an in-use building. The framework demonstrated between BIM and a predictive building energy performance model provides a contemporary framework for information generation and sharing between engineers and Energy Performance Modelling specialists. Demonstration of efficient performance data handling, error removal and pattern finding using basic building performance metrics identifies opportunities for performance improvement and potential starting points of further investigation.

The number of factors to be considered in implementing BIM for performance management currently are significant, reducing the potential for its widespread adoption. Incremental changes to current processes to support implementation in this way will develop during its wider adoption, with the findings presented here proposing the necessary steps required to achieve BIM application to building energy performance management.

Contents

List of figures

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List of publications

The following papers, included in the appendices, have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the research.

[Conference] Paper 1 (see Appendix A)
Gerrish, T., Ruikar, K., and Cook, M. J. (2014). *Cross discipline knowledge transfer for concurrent BIM adoption in an engineering organisation.* In: Proceedings of the 2014 CIB W55/65/89/92/96/102/117 & TG72/81/83 International Conference on Construction in a Changing World. 4th-7th May 2014. Sri Lanka: CIB.

[Journal] Paper 2 (see Appendix B)
Gerrish, T., Ruikar, K., Cook, M. J., Johnson, M., and Phillip, M. (2017). *Using BIM capabilities to improve existing building energy modelling practices.* In: Engineering, Construction and Architectural Management 24 (2). DOI: 10.1108/ECAM-11-2015-0181.

[Conference] Paper 3 (see Appendix C)
Gerrish, T., Ruikar, K., Cook, M. J., Johnson, M., and Phillip, M. (2015). *Attributing in-use building performance data to an as-built building information model for life-cycle building performance management.* In: Proceedings of CIB W78. 27th-29th October 2015 Eindhoven, The Netherlands: CIB.

[Journal] Paper 4 (see Appendix D)
Gerrish, T., Ruikar, K., Cook, M. J., Johnson, M., and Phillip, M. (2017). *Analysis of basic building performance data for identification of performance issues.* In: Facilities 35 (13/14). DOI: 10.1108/F-01-2016-0003.

[Journal] Paper 5 (see Appendix E)
Gerrish, T., Ruikar, K., Cook, M.J., Johnson, M., Phillip, M., Lowry, C (2017). *BIM application to building performance visualisation and management: Challenges and potential.* In: Energy and Buildings 144. DOI: 10.1016/j.enbuild.2017.03.032.

Additional publications

Additional publications made throughout research but not included within this document are listed below with full references.

[Magazine Article] – Gerrish (2013)
Gerrish, T. (2013). *Integrating energy performance modelling into building operations using BIM.* In: Innovation & Research Focus 5. URL: http://www.innovationresearchfocus.org.uk/Issues/95/IRF95_CICE.html (visited on 2016-02-23).

[Magazine Article] – Gerrish (2014)
Gerrish, T. (2014). *Bolt-on performance.* In: CIBSE Journal, pp. 8–10. URL: http://www.cibsejournal.com/archive/PDFs/CIBSE-Supplement-2014-06.pdf (visited on 2016-02-29).

[Journal Editorial] – Gerrish et al. (2016a)

Gerrish, T., Cook, M. J., and Ruikar, K. (2016). *BIM for the management of building services information during building design and use.* In: Science and Technology for the Built Environment 22 (3), pp. 249-251. DOI: 10.1080/23744731.2016.1156947.

[Book Chapter] – Gerrish et al. (2017a)
Gerrish, T., Ruikar, K., Cook, M J., Johnson, M., Phillip, M (2017). *Use of BIM in Construction.* In: Advances in Construction ICT and e-Business. Ed. by S. Perera, B. Ingirige, K. Ruikar, and E. Obonyo. Routledge.

1 Introduction

This chapter sets out the context of the research undertaken and introduces the subject, describing the justification for research, aim and objectives, and organisational implementation of this work.

1.1 Background

The definition of Building Information Modelling (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 (Azhar, 2011), but fundamentally it describes the exchange, interpretation and utilisation of meta-data surrounding a Computer Aided Design (CAD) model, supporting multiple functions for various stakeholders in a construction and operations process; otherwise described as a Common Data Environment (CDE). In the context of this research, building information is the key element being investigated, and that which is explored in depth. The information being looked at specifically is that which describes how a building performs in terms of its energy consumption during use, and impact on the occupants comfort for modelling and simulation, and throughout its lifetime. The means by which that information can be made accessible is the primary underlying theme of this work, feeding into a wider body of knowledge facilitating effective design and use of more efficient buildings.

Distinction must be made at this point, to separate the various definitions of BIM and clarify the scope of research included. Firstly, BIM is an all encompassing acronym, representing all information generated within Architecture, Engineering and Construction (AEC) projects and their ongoing operations; however, it is not a definitive description that can be applied to a specific situation (not least because it particularly refers to buildings, in a subject where infrastructure and the setting in which the building is located play a large part in the information describing a building). In conjunction with BIM, an increasing list of acronyms, related topics and sub-topics have been related to BIM describing particular aspects of information relevant to built projects. Even the acronym BIM has been modified to refer to these (for example, Asset Information Modelling (AIM) and Project Information Model (PIM) describing various portions of information modelled at different stages of a project life-cycle). Secondly, until recently, focus has been kept on the benefits use of a CDE for building information has on design and the challenges in

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*To avoid redundancy of the word 'model' when following Building Information Modelling, the acronym BIM may be interpreted contextually as either Building Information Modelling or Building Information Model.

implementation of such environments. The benefits it has on the long-term operation of a building post-completion are now being realised. Starting from the effective communication of design intent to facility operators and occupants, to the day-to-day maintenance and upkeep of that facility, the widespread adoption of BIM throughout the AEC industry has prompted specification of handover documentation in the form of models with meta-data to enable more effective Facilities Management (FM).

Performance management of a building spans both design and operation of its life-cycle. Initially, its form can be optimised to reduce demand for lighting, heating and cooling, then later its performance simulated using Energy Performance Modelling (EPM) to explore design options in detail, and determine effective operating strategies. During use, the performance of that building is then monitored using a Building Management System (BMS) and can be further optimised through continual Building Energy Management (BEM) to account for changes in use, climate and equipment. This entire process is one that is becoming more commonplace for new buildings, with the advent of accessible EPM tools and intelligent monitoring systems, yet there is still need for expert input into design and optimisation. This is exemplified through schemes such as Soft Landings (where handover of a building to its occupants is made with its effective operation a forefront concern) and Post-Occupancy Evaluation (POE) which investigates in-use buildings to explore potential for improvement and occupant satisfaction.
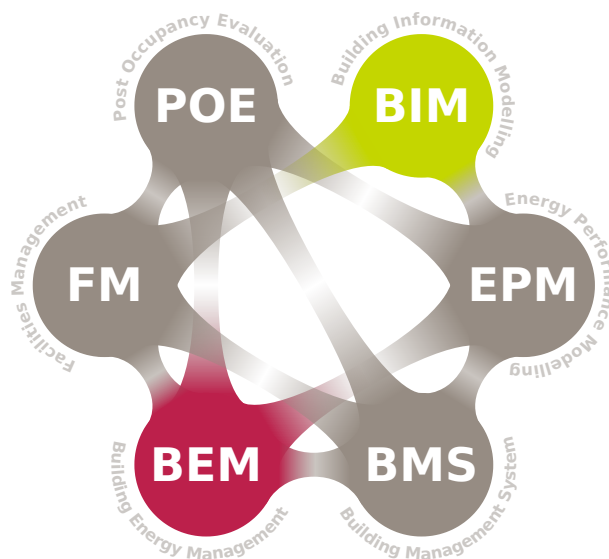
Figure 1.1: Major themes relevant to the research undertaken

Given the breadth of topics mentioned, the themes explored here (each of which is in some way impacted by BIM) are indicated in Fig. 1.1. In places these share common aspects (for example, BEM and FM both relate to the operational management of a building, while the introduction of available data into this relationship through BIM means it forms part of the loop joining BIM to the incremental improvements in ongoing BEM and operational efficiency improvements. The addition of extensive descriptive and prognostic databases to this process suggests BIM will augment the entire design and use stages of a building's life-cycle, providing a comprehensive database to support building designers and users in better managing the energy performance of their facilities.

1.2   The industrial sponsor

This research was part funded by BuroHappold Engineering, a multi-disciplinary engineering consultancy, offering a wide range of services in design, planning, project management and consulting under the broad areas of buildings, infrastructure and environment. Founded in 1976 by eight partners, the company has grown to over 1800 employees in 30 offices around the world. BuroHappold does not have a mission statement, but its founding principle of collaboration across disciplines as defined by its founder Professor Sir Edmund (Ted) Happold is outlined in this quote from Addis and Walker (1998):

> '*What I know about engineering is that it has to be a group activity. The best work is done by the most diverse group of talents that can live together... Clearly good projects are all stories of personal relationships – people work with you and you with them – because you both think you will perform better by putting your skills together and because you think it will be fun.*'

BuroHappold's involvement in construction engineering can range from the earliest stage of a project's development, advising clients on project management, to being brought in post-completion to assess performance and optimise operations (Fig. 1.2). This scope collects a wide range of specialisms applied across a building's life-cycle; however, the implementation of BIM remains a challenge to successfully implement due to its far reaching implications. The role BuroHappold takes differs between projects, meaning involvement in a building design process may start or finish at various stages of the project's development. Ensuring effective use of BIM, while adhering to different projects standards and replicating success across projects, is where understanding of how best to implement BIM tools and processes is essential.
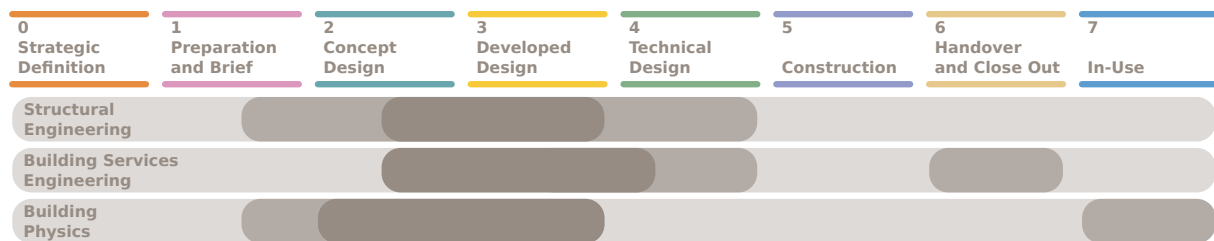
Figure 1.2: BuroHappold involvement in the construction engineering design process

At its broadest, the scope BuroHappold envisages for BIM is that all information generated across contributing engineering disciplines be made available between all design platforms through a common means (under development within the organisation as the BuroHappold Object Model (BHoM) but known widely as a CDE). Methods of integrating building energy performance information into this model are currently being developed, but there is no means for data collected from building post-handover to feed into this and be used to inform design decisions in later projects. The research presented here shows an incremental step in reaching that goal; being able to link the design model to an as-built building's BMS, and portray its historical performance in context with our input to that performance. In doing this we can close the loop between design and operation in current projects, and use a lessons-learned approach to make improvements in subsequent projects.

The expertise contained within BuroHappold is only effective when utilised to benefit clients, the stakeholders they represent and the wider environment; and where possible, contribute to the reduction of energy consumption in the AEC sector (Nguyen and Aiello, 2013). Taking steps to reduce this consumption, and make the building's we design better for their occupants is a focus not just of BuroHappold, but of the construction industry as a whole.

1.3 Need for the research

Effective management of a building's in-use performance requires an understanding of the physical processes taking place within and about that building. In particular, how building services provide occupant comfort, the fabric maintaining this comfort, and the equipment and space utilisation that contribute to the demand for energy. The balance between energy required for conditioning, and the factors contributing towards this demand determine the performance of a building, where more efficient buildings demand less due to careful form, function and operation planning.

In efficient buildings, the potential for misuse both implicit and explicit is compounded due to the often narrow band in which operational efficiency is maximised (Day and Gunderson, 2015; Mumovic and Santamouris, 2009). Balance between systems and occupant interactions are designed such that the building is symbiotic to its occupant's needs and demands, and performs efficiently when this symbiosis is respected and all processes operate within their expected means. While highly efficient buildings are great examples of misuse and changes to this relationship reducing overall efficiency, the majority of building stock also succumbs to improper operation contributing to excess energy consumption and reduced occupant comfort. The phenomenon known as the 'performance gap' has been explored in depth (Fowler and Rauch, 2008; Turner and Frankel, 2008; Torcellini et al., 2004), with reasons for its existence now well established (Menezes et al., 2012). This subject is examined in Section 2.2.

Efforts to reduce this gap, of which this work is partially contributing, are now being implemented in traditional (or non high-performance) building projects, wherein it is expected that upon handover of the building the designers provide the owners, occupiers or operators the means with which to effectively manage their new building. Soft Landings were originally suggested in the UK by Way and Bordass (2005) and further developed into a scheme now adopted by UK government (Way et al., 2009) to address the need for better handover and familiarisation with buildings upon completion (Cabinet Office, 2013). Part of these state benefits of more effective handover as reduction in time needed to reach as-designed performance, reduced running costs and generation of feedback to those responsible for the building's design. Closing the loop from completion back to design could potentially mean the next building designed does not have the same faults as the previous, and continual learning by designers would lead to better, more efficient and lower energy demanding buildings (Mathew et al., 2015; Torcellini et al., 2004).

The opportunity to improve future projects by learning from the past is not the only benefit a better understanding of existing buildings could give. The tools used to create these buildings are now generating vast amounts of data describing it at various stages of its development. During design this data is used by multiple stakeholders to further

their input. For example, an EPM may be created to simulate performance to identify the heating and cooling needs of the building. Until now, these predictions have been useful, but often inaccurate following changes in design at a later stage or changes in use during operation (Bordass et al., 2001). Ryan and Sanquist (2012) suggest that while the methods of simulating discrete yet dynamic performance have been improving, predicting occupant behaviour remains difficult due to the time and cost required to collect and make sense of detailed logs of these behaviours and their impact is prohibitive (Ham and Golparvar-Fard, 2013). Here, interoperability between existing data frameworks about which data could be attributed and visualised could potentially reduce the time and subsequent cost needed to explore such data; of which BMS and BIM provide that data and framework respectively.

The problems currently facing those attempting this link between data of various forms, all describing how buildings operate, and reinforcing the need for this research include:

– Inadequate interoperability between design tools limiting effective transfer of information for design;
– A skills gap between those who can and cannot effectively use BIM supporting tools and processes;
– Few links between BIM and BEM tools that can be implemented without extensive time, cost and effort;
– Inability for the building end-user to clearly see how and where their behaviour impacts on the performance of their building; and
– Lack of data integrity from BMS, leading to inaccurate performance representation.

An extensive literature review presented in Chapter 2 further demonstrates the need for this research, which in summary shows that:

– Research into BIM use for energy performance improvements is primarily focused on design stage improvements for sustainability accreditation, and early design form optimisation;
– The few efforts to integrate BIM into the operations stage of a building's life-cycle, focus on asset management and the handover of comprehensive asset models describing objects within that building for FM;
– Examples where BIM has successfully been linked to the energy performance of buildings are few, with those available only demonstrated on small control studies; and
– Insufficient guidance is available for building designers and occupants to utilise the data made available to them through BIM to understand how their building is and should be performing.

The findings presented here are relevant to the wider AEC industry, as what may be applicable to projects undertaken by BuroHappold is also applicable to operators of buildings who will soon be able to access comprehensive models of their buildings (HM Government, 2013; Cabinet Office, 2011) in conjunction with monitoring systems designed to manage, but not optimise performance. The research here provides organisations and individuals considering a more effective means of BEM, a greater understanding of the information required and challenges they may face in implementing such schemes.

1.3.1 Mandated use of BIM

BIM to the standard of Level 2 (defined by the Cabinet Office (2011) and the Bew-Richards Maturity model (BIM Task Group, 2011)) within the UK has recently been mandated for all centrally procured government projects. This requirement, stemming from wider aims to reduce the capital cost of built environment projects also targets a reduction in carbon emissions by 20% by 2020 (DECC, 2011). As outlined in industry-wide assessment by Latham (1994) and Egan et al. (1998), the construction industry's capabilities and adaptability to new processes and technologies to support more effective design and operation requires impetus to promote change, which these mandates provide.

The gradual widespread adoption of BIM as a standard design development process means the availability of information will increase, and the potential for its implementation in multiple domains must be understood in order to facilitate its effective use.

1.4 Research scope

The scope initially defined by the industry sponsor was refined during investigation of the relevant subject areas to cover aspects of both design and operation of a non-domestic building, and the development and implementation of a tool demonstrating potential links to be made between these areas. This sequential scope utilised outputs from separate work-streams to feed into realisation of the potential for BIM use in understanding building energy performance data. Key points throughout the design and operations processes examined here are identified in Fig. 1.3.
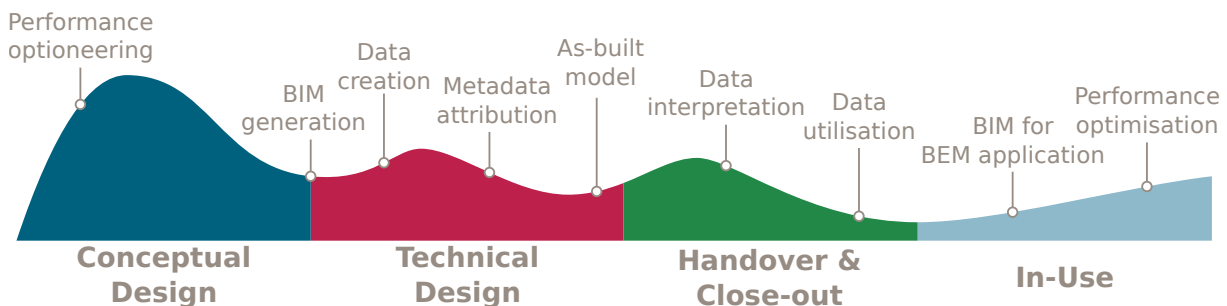
Figure 1.3: Research scope in context with a building life-cycle (showing the proportion of information generated during each stage)

From the initial scope of this research project objectives were proposed and adjusted according to changing needs of BuroHappold, and given the time and resources available were tailored to evaluate the performance of a particular building around which this research was applied. Making sense of the performance of this building designed structurally using BIM processes is the main application of the research described here, with lessons learned from investigation of various aspects of this process feeding into the findings and outcomes.

A non-domestic building was the primary focus for this research, due primarily to information available and context of that building in the ongoing development and implementation of BIM by the research sponsor. Non-domestic buildings are designed, built and operated with much more variety in composition (due to their differences in purpose) and inclusion of post-occupancy monitoring systems than domestic buildings; making them

more suitable for exploration of interconnection between as-designed information in a BIM environment, and operational information describing energy performance. As a result, the scope of this research is mainly applicable to non-domestic buildings where design information is developed using BIM technologies and processes and is where implementation of findings is likely to have the greatest impact.

Research scope covers the core subject of BIM and related areas currently being investigated in industry and academia, for their utilisation of BIM to support new and innovative methods of using data in the BIM environment. The subjects therein included:

- Building Information Modelling (BIM) as the CDE for attribution of building performance data;
- Data transfer between design tools facilitating effective design supported by BIM;
- Facilities Management (FM) use of design information and BIM for managing building performance;
- Energy Performance Modelling (EPM) and BIM for optimisation of performance during design;
- Building Energy Management (BEM) for optimisation of performance during operation (including Continuous Commissioning (CC));
- Post-Occupancy Evaluation (POE) of building energy performance and occupant comfort; and
- Knowledge Management (KM) for the understanding and actioning of improvements from understanding of building energy performance.

Each of these components are explored in context with the current state of BIM in the AEC industry in non-domestic buildings, to portray this subject area holistically and outline the requirements for further development in this area.

1.5 Aim and objectives

The aim of this research was to explore the use of BIM as a tool to support the management of information describing a building's in-use performance during its occupation, utilising monitored and design data. The objectives described here were split into tasks, the details of which are explained further in Section 1.6. The four main objectives were:

1.5.1 Objective 1

The first objective constituted the exploratory phase of research, topic familiarisation through a literature review and further research subject definition. This exploratory phase established the scope of research undertaken and identification of the current benefits and barriers to implementing BIM as an energy performance management tool at different stages of a building's life-cycle. The sub-tasks for this objective were:

- Review of current state of BIM in design and in the operational performance of buildings;
- Review the BIM capabilities and adoption strategy of key disciplines within Buro-Happold;

– Identify the building performance information development process, creating a process for information generation and exchange; and

– Using findings from Objective 1, re-evaluate initial objectives to benefit BuroHappold's requirements.

1.5.2 Objective 2

This identified the data available for the building around which this research was focussed, and constituted the creation of building energy performance data attributable to a BIM environment.

This research was carried out between March 2013 and January 2016 to allow for seasonal commissioning to take place, and data collection over at least a full year (accounting for initial commissioning, seasonal commissioning and fault rectification in the first year of a building's life-cycle). The sub-tasks for this objective comprised the:

– Development of a representative BIM of the subject building;

– Testing of parametric data attribution to modelled objects, including object metadata and time-series performance data;

– Analysis of a building's recorded in-use energy performance data and creation of a representative EPM; and

– Extensible parameter attribution to the as-built model, representing the in-use building in a BIM environment.

1.5.3 Objective 3

Objective 3 focused on developing a method for linking BIM with monitored operational data from a BMS to support exploration, understanding and optimisation of building performance. This constituted the implementation of findings from the previous objectives to achieve the output required of this objective. The sub-tasks for this objective were:

– Investigate the performance issues encountered in the building to which this research is being applied;

– Assess the representative EPM against recorded BMS data;

– Develop a method of linking the BIM to the recorded BMS building energy performance data; and

– Implement and test the effectiveness of BIM for energy performance management of a building.

1.5.4 Objective 4

The final objective collected findings from all tasks carried out and applied these to the development of a BIM-based tool that could assist with the management of a building's energy performance. The evaluation of this tool indicated its application for understanding and making changes to a building's operation to reduce energy consumption, and assessed potential for application to other buildings. The implications this has for the industry sponsor and wider AEC industry in utilising BIM for further use in

building energy performance management is considered and evaluated. Finally, procedural recommendations were made for recreating this in future projects, with recommendations proposed for areas of future research. The sub-tasks for this objective were:

– Develop and apply BIM/BMS performance data management tool;
– Summarise the tool development process and identify the critical factors necessary for replication;
– Quantify the impact of the tool to the industry sponsor and building end-user; and
– Make recommendations for the ongoing application and development of BIM during design and operation.

1.6 Structure of thesis

The objectives and their sub-objectives were approached using an ontology engineering approach described by de Nicola et al. (2009), dividing the subject matter into distinct domains to examine the relationship between the concepts therein, and later rebuilding these into a method utilising outputs from each to achieve the goal set out in the original research proposal (described in Section 1.3).
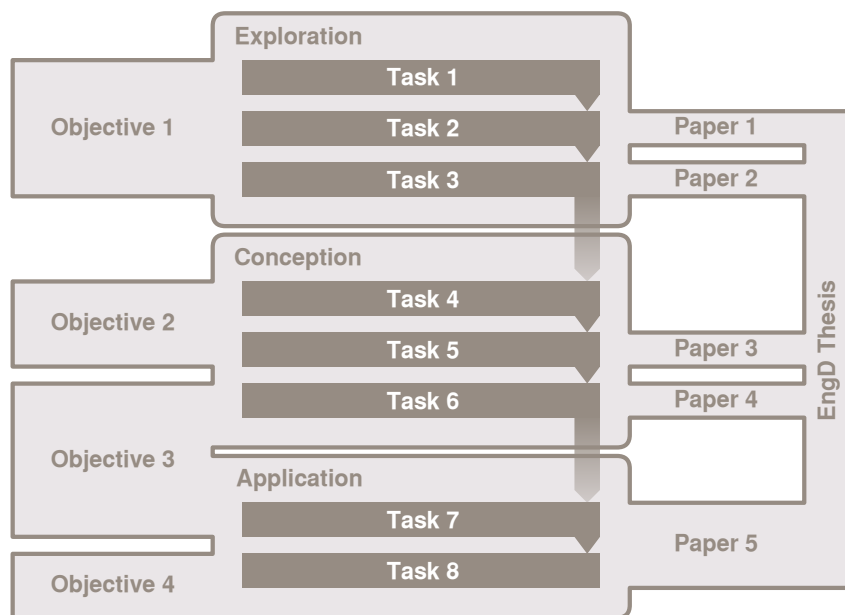
Figure 1.4: Research objective relationships

The tasks follow a primarily sequential path, developing upon the outputs of the previous distinct bodies of work to form a coherent proposal for the use of BIM to support management of building energy performance information. A broad review of literature and the current capabilities of BuroHappold (Objective 1) were followed by the investigation of information generation and sharing during building performance design (Objective 1). The monitoring of a building's performance and creation of representative BIM and EPM models (Objective 2) was undertaken to provide a set of data about which to experiment with data by means of BIM model. This led to further research into the capacity of BIM for the storage of time-series building performance information

(Objective 2). This provided the necessary understanding required to develop a BIM and building performance data management tool (Objective 3) and identify where deficiencies in building performance could be identified using such a tool (Objective 3), culminating in the application, evaluation and synthesis of this knowledge (Objective 4). The tasks carried out and their individual outputs are shown in Fig. 1.4.

Summaries of each task within these objectives are given in Chapter 4.

1.7 Publications

Several peer-reviewed papers were written as part of research progress documentation and to disseminate findings, summarised in Table 1.1 with full references and links to these in full.

Table 1.1: List of publications

Paper	Title	Reference
[Conference] Paper 1 (Appendix A)	Cross discipline knowledge transfer for concurrent BIM adoption in an engineering organisation	Gerrish, T., Ruikar, K., and Cook, M. J. (2014). *Cross discipline knowledge transfer for concurrent BIM adoption in an engineering organisation.* In: Proceedings of the 2014 CIB W55/65/89/92/96/102/117 & TG72/81/83 International Conference on Construction in a Changing World. 4th-7th May 2014. Sri Lanka: CIB.
[Journal] Paper 2 (Appendix B)	Using BIM capabilities to improve existing building energy modelling practices	Gerrish, T., Ruikar, K., Cook, M. J., Johnson, M., and Phillip, M. (2017). *Using BIM capabilities to improve existing building energy modelling practices.* In: Engineering, Construction and Architectural Management 24 (2). DOI: 10.1108/ECAM-11-2015-0181.
[Conference] Paper 3 (Appendix C)	Attributing in-use building performance data to an as-built building information model for life-cycle building performance management	Gerrish, T., Ruikar, K., Cook, M. J., Johnson, M., and Phillip, M. (2015). *Attributing in-use building performance data to an as-built building information model for life-cycle building performance management.* In: Proceedings of CIB W78. 27th-29th October 2015 Eindhoven, The Netherlands: CIB.
[Journal] Paper 4 (Appendix D)	Analysis of basic building performance data for identification of performance issues	Gerrish, T., Ruikar, K., Cook, M. J., Johnson, M., and Phillip, M. (2017). *Analysis of basic building performance data for identification of performance issues.* In: Facilities 35 (13/14). DOI: 10.1108/F-01-2016-0003.
[Journal] Paper 5 (Appendix E)	BIM application to building energy performance visualisation and management: Challenges and potential	Gerrish, T., Ruikar, K., Cook, M.J., Johnson, M., Phillip, M., Lowry, C (2017). *BIM application to building performance visualisation and management: Challenges and potential.* In: Energy and Buildings 144. DOI: 10.1016/j.enbuild.2017.03.032.

1.8 Structure of thesis

Chapter 2 discusses the current state of BIM in the AEC industry in context with the energy performance design and management of non-domestic buildings, and presents

a detailed review of the subjects therein and their relationship with BIM.

Chapter 3 sets out the methodologies applied during research, and their justification in relation to the work carried out. Consideration of alternative methodologies is given here, with predication of the most suitable made.

Chapter 4 provides a detailed account of the research through which the work undertaken is summarised, describing the individual tasks as defined in Sections 3.5.1 to 3.5.4 and working through the decisions made, justification of those and the outcomes from each individual research task.

Chapter 5 discusses the main findings of the research. It includes a critical evaluation of the research presented and the impact of BIM implementation for building energy performance optimisation on the industry sponsor and the industry as a whole. Conclusions are presented with a number of recommendations for future research suggested.

Appendices A to E contain 5 peer-reviewed papers published during this work, to which references are made throughout this document.

1.9 Summary

This chapter introduced the research and highlighted its reasons for investigation, outlined the aim and objectives, their justification and the outputs of these. An extensive literature review of the subject area is now given in Chapter 2.

2 Review of related literature

This chapter presents the current state of Building Information Modelling (BIM) use in the Architecture, Engineering and Construction (AEC) industry, in context with its utilisation in the reduction of energy consumption of buildings. Due to the all encompassing nature of BIM as a subject, a brief introduction to it is made, then aligned with the wider body of knowledge surrounding building performance design, management and optimisation. This is then split into the relationships between BIM building energy performance during design, handover, operation and the subjects therein.

2.1 Building Information Modelling

Identification of the need to more effectively integrate different design disciplines and stakeholders in the AEC industry was noted by Latham (1994) and Egan et al. (1998). The method with which this integration is being applied is through BIM. BIM is the process of capturing meta-data throughout the planning, design and construction stages of a building's life-cycle, in a Common Data Environment (CDE). Eastman et al. (2011) define BIM as one or more virtual models of a building, supporting its design through progressive stages to better enable the analysis and control of design, construction, fabrication, and in-use activities. Part of this process is the facilitative access to information relevant to all stakeholders for the purposes of making design decisions (Jung and Joo, 2011). Examples of the type of parametric data stored within a BIM environment could be the building's form, fabric, systems and definition of their maintenance and usage. The meta-data attached to those examples further describe the form of the projects, composition of materials in the fabric, distinct components making up a system, how these are maintained during their life-cycle, and instructions for their use (Long et al., 2011).

2.1.1 State of the industry

Adoption of BIM as a means of building design has been implemented across the AEC industry since the concept of virtual design and construction was first suggested (Quirk, 2012), though not necessarily called BIM. In recent years, that application has grown extensively, with Hartmann and Fischer (2008) demonstrating its benefits of higher productivity and greater stakeholder engagement across contributors. Additional benefits have also been identified as enhanced coordination and collaboration between design disciplines (Singh et al., 2011); clash detection for building geometry and systems (Bryde et al., 2012); schedule and cost optimisation (Lee et al., 2014; Kim et al., 2013); reduced drafting time (Matthews et al., 2015); and improved information accessibility (Jung and

Joo, 2011).

Research by McGraw Hill Construction (2010b) shows the perceived benefit of BIM, using industry surveys to understand how BIM adopters and users are experiencing changes in working methods without quantifiable measurement in output. This survey showed adoption rates growing throughout all areas of construction and building design. Collaboration between designers for effective delivery of a building has been identified by Azhar (2011) and Gu and London (2010) for savings of cost and time throughout design. Each observes the need for adoption to be considered by all those affected (Arayici et al., 2011), as with all adoptions of new methods of working and implementation of supporting technologies (Gonçalves and Gonçalves, 2012).

UK construction strategy

In context with the wider UK governments industrial strategy for construction (HM Government, 2013), BIM plays a role in the potential for greater productivity and reductions in costs, through improved information flow and greater collaboration. The primary aim tied into a commitment to reduce costs of public sector construction by 15-20% by 2015; however, proof of this achievement is unavailable. The implementation of BIM has been mandated to the standard of Level 2 (according to the Bew-Richards Maturity model (BIM Task Group, 2011)) for all centrally procured government projects as defined by the Cabinet Office (2011).

HM Government (2013) also aims to progress BIM implementation to Level 3, a currently undefined standard of information modelling, development and exchange through the 'Digital Built Britain' strategy (HM Government, 2015). This sets out the potential next steps in creating open data standards for sharing of information, establishment of contractual frameworks to support BIM implementation and encourage collaboration, and drive growth in this area by training and developing a collaborative culture. A key element of these ambitious targets is the focus on infrastructure (moving from buildings, through to transportation, water power and people), looking beyond buildings toward their setting and place amidst the wider built environment, an area to which BIM is yet to fully be applied (Bradley et al., 2016). Delivery phases for Level 3 BIM are defined within the Digital Built Britain document sequentially as; "enabling improvements in the Level 2 model", "enabling new technologies and systems", "enabling the development of new business models" and "capitalising on world leadership".

2.1.2 Technology and processes

The technology supporting the implementation of these new capabilities in construction project delivery is an integral part of BIM, and often misunderstood to be what BIM represents (Hamil, 2011). However, the technology enables the collaboration and utilisation of information generated during a building's design and lifetime, and is put forward by Eastman et al. (2009) as integral to modern building design in the AEC industry. Use of BIM as an information-aggregating tool uses distinct models for various purposes during building design, federated in a CDE describing multiple aspects of a building's composition. However, its use as a repository for information during building use is still relatively unexplored (Gerrish et al., 2015). The exchange of information between these composite

environments prior to their amalgamation, to support the development of a 'single source of truth' representing the actual finished building requires interoperability and exchange capabilities between model creation tools (Choi and Kim, 2011).

Several modelling environments have been created which use the de-facto standard Industry Foundation Class (IFC) as an exchange format with which BIM data can be recorded, shared and interpreted by other modelling tools (BuildingSMART, 2013). This platform-neutral open format supports interoperability between these tools, with implementation now widespread. IFC was developed as an extensible exchange format moving from closed and proprietary formats employed in the 1970s (Laakso and Kiviniemi, 2012) to a generic framework for information storage in the Standard for the Exchange of Product Model Data (STEP) format. More recent endeavours have aimed to move IFC towards existence as a "useful minimum" (Hietanen and Lehtinen, 2006), reducing the scope of content to that necessary for effective implementation. Expansion of this scope is now therefore transferred to Model View Definitions (MVDs), which contain discipline specific information supplementary to the core elements of information within the IFC schema. Laakso and Kiviniemi (2012) discuss the limitations of the IFC standard as it was implemented in 2012, though it is still prescient in the current AEC industry given the slow adoption of it a common information exchange method. Those identified included ambiguity within the open standard through its use of STEP and reliance on software capability to interface correctly with this format and its part in the paradoxical loop preceding the need for market demand for the open standard, and following industry's need to identify measurable benefits of integrated BIM.

The limitations of this format for accurate reproduction between platforms include restrictions on the ability to transfer modelling tool-specific functionalities, reliance on multiple modelling tools to record and interpret the information correctly, and the amount of information stored in this way (Gerrish et al., 2015). Additional functionalities have been developed using the IFC format, of which those relating specifically to building performance target the capacity to support simulation of the building, using Energy Performance Modelling (EPM) from models generated in BIM environments (Hitchcock and Wong, 2011; Dong et al., 2007). In this way, the BIM could be re-used to create building energy performance simulation models, of which more detail is given in Section 2.2.1.

In addition to information transfer, the use of BIM has been proven by Giel and Issa (2013), Forgues et al. (2012), and Neelamkavil and Ahamed (2012) to reduce the number of clashes experienced on construction projects and therefore the amount of cost attribution to error correction during building design and construction. Research by Gallaher et al. (2004) shows that these areas of interoperability are a large contributor to undue cost in the construction industry. This lack of interoperability between systems, elements of design and various forms of information is a contributing factor to the 'performance gap' (de Wilde, 2014; Menezes et al., 2012; Turner and Frankel, 2008; Bordass et al., 2001); with Menezes et al. (2012) noting that " management decisions . . . were observed to have a significant impact on the tenant consumption". This is an area closely related to the implementation of BIM both during design and operation, where BIM is predicted by Volk et al. (2014) to have its biggest impact.

2.2   Building energy performance

The performance of a building regarding the energy it consumes, and the impact various methods of its operation have on the comfort and well-being of occupants is of vital importance not just to those occupants or building operators, but on a global scale in terms of the impact those buildings have on the wider environment. The Energy Performance of Buildings Directive (EPBD) created by the European Parliament and Council of the European Union (2002) aimed to align European Union (EU) laws to a common goal of reducing the energy consumed by buildings, and has since been implemented across many EU countries (Maldonado, 2015). Within the UK, these directives have been used to develop national guidance and regulation to reduce building energy consumption (using certification to expose building energy consumption (Zero Carbon Hub, 2013)), and BIM has been suggested by Tuohy and Murphy (2015), Azhar et al. (2009), and Krygiel and Nies (2008) as a means to better manage this.

According to the DECC (2015), the average annual electricity and gas use intensities for non-domestic buildings in the UK are 116kWh/m^2 and 193kWh/m^2 respectively. Using recent figures from the DECC (2016), these result in an average annual cost per square metre of £12.06 for electricity and £5.31 for gas across all non-domestic buildings. Equating the energy consumed by a building throughout its lifetime to the energy expended in building it, the opportunity for in-use improvements through better management of a building is large (Sartori and Hestnes, 2007), where 90-95% of that buildings life-cycle energy is accounted for during operation. In addition to the cost to power, heat and cool a facility, there are also ongoing maintenance costs (Hughes et al., 2004), which can be reduced through greater understanding of the changes in the levels of performance experienced (Cao and Pietiläinen, 2013; Ulickey et al., 2010). Monitoring of conditioning equipment to mitigate against inefficient operation would both reduce cost of conditioning, and focus improvement on the longest term of the building's life-cycle and energy consumption.

Reviewing Building Energy Management (BEM) through a BIM lens, the following section explores the application of BIM to support reduction in energy consumption, and the continual improvement of a building's overall performance at the design development, handover and operational phases of a building's life-cycle. Its application at various stages of this process is indicated in Fig. 2.1.
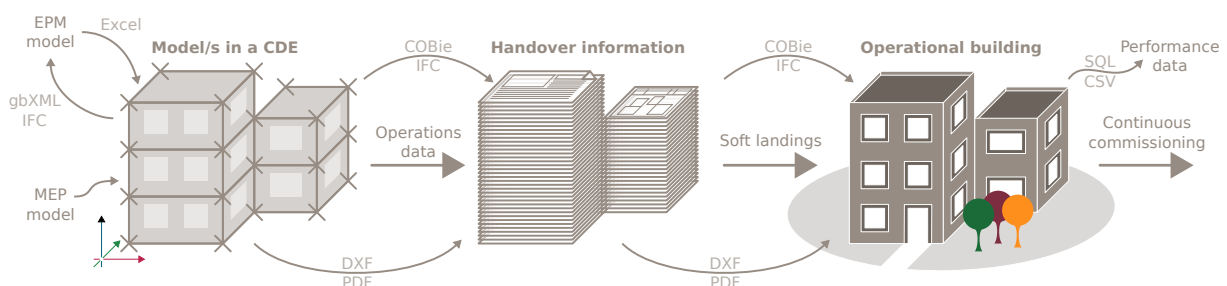
Figure 2.1: Data describing a building's performance throughout design, handover and building operation currently in relation to BIM

2.2.1 During building design

Building performance information generated during design consists of information describing building composition, and the performance of equipment providing some function in the heating, cooling, ventilation of the spaces making up that building. Dynamic information is also generated, describing how these systems and components interact throughout a representative year (defined from standard weather files for the location in which the building is situated), which is used to approximate sizes of that equipment and adjust the building's composition to suit its requirements (Clarke, 2001). Pauwels et al. (2012) describe these sources of information in the context of an already functioning building (Fig. 2.2), with the same information types used for EPM during design (Yoshino, 2010).
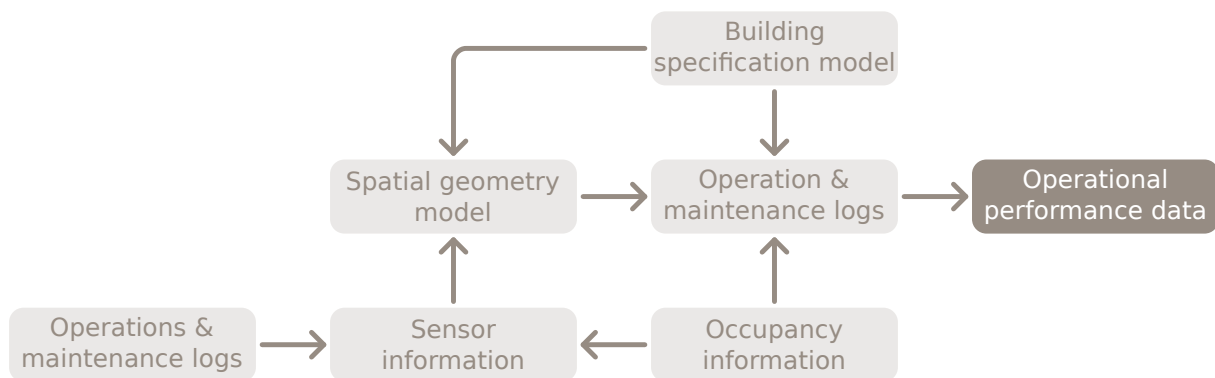
Figure 2.2: Energy Performance Modelling data sources (based on Pauwels et al. (2012))

Effective use of this information can support the design of a building's energy performance (Kneifel, 2010; Bakens et al., 2005; Torcellini et al., 2004; von Paumgartten, 2003; Stern, 1997), with scope for improvement in this process recognised by several previous industry wide studies (DECC, 2012; Carbon Trust, 2011; Zero Carbon Hub, 2010; Turner and Frankel, 2008). During design, use of BIM to support this may be used as a means through which design information could be shared to effectively support communication of design intent, and reach an efficient design by collaboration between the multiple stakeholders involved in that process (Gerrish et al., 2016c; Shafiq et al., 2013).

Building performance design

During design, the performance of a building is determined based on the requirements of the design brief, and physical and legislative restrictions imposed by its location, form, composition and end-use (Hensen and Lamberts, 2011; Clarke, 2001). The prediction of the most efficient outcome based on these factors is achieved using EPM for simulation of proposed designs and quantification of the building's performance for use in later design, assessing operational strategies and form finding. Widespread use of BIM to support this is yet to happen (Gerrish et al., 2015), potentially due to those perceived costs of creating intelligent, sustainable buildings (DECC, 2012; McGraw Hill Construction, 2010a). Identification of this slow uptake was made by Nam and Tatum (1988), who recognised the complexity of integrating a wide range of composite processes with potential for future improvement; yet more recent work by Dowsett and Harty (2013) demonstrates that

current capabilities still do not meet that potential. The majority of development in this area has taken place in the use of BIM for analysis of a building's holistic sustainability through accreditation (Beach et al., 2015), an area where quantifiable metrics from existing models can be analysed for compliance with certification schemes such as Building Research Establishment Environmental Assessment Method (BREEAM) (Ilhan and Yaman, 2015), Leadership in Energy and Environmental Design (LEED) (Jalaei and Jrade, 2015) and Green Star (Gandhi and Jupp, 2014). As such, practical energy performance benefits demonstrated from implementation of BIM have been overlooked in favour of more immediately quantifiable performance indicators (Gerrish et al., 2016a).

Building performance prediction

Accurate prediction of a building's as-built performance using EPM relies on an accurate depiction of that building, though during design many assumptions must be made, particularly regarding occupant activities and behaviour (Menezes et al., 2012; Wang et al., 2012). Wholly accurate modelling of complex and unpredictable operations requires multi-domain approaches, using all available data sources (Wallis et al., 2009), and even then there is some uncertainty of the accuracy of the predictions made (de Wit, 1995). Accessibility of the most accurate information is one area in which BIM is assisting simulation, providing an environment from which the most recent design data is used to produce an energy model (Gerrish et al., 2016c). However, the BIM environment does not just disappear upon completion and handover, with scope for information attribution in conjunction with parallel simulation of a building's performance to provide an ongoing performance prediction (Bazjanac, 2008).

BIM integration with building energy performance design

Attempts to embed EPM within BIM environments have been made, most notably as add-ons to their existing functionality. For example, the popular BIM authoring tool Revit (Autodesk, 2015c) can send geometry and building performance defining criteria such as location, space function and Heating, Ventilation and Air-Conditioning (HVAC) system configuration to its cloud-based Green Building Studio (Autodesk, 2015b) for energy analysis. At an early stage of design, this can help the designer make informed design decisions based on energy efficiency of the whole building, making energy performance simulation accessible to designers without sustainable design expertise (Zanni et al., 2014); however, Stumpf et al. (2011) and Che et al. (2010) suggest that care must be taken to ensure interpretation of the output from this is made correctly. Basic analysis using such tools are useful, yet this functionality is only viable as an analysis tool during conceptual modelling due to the simplifications made to the building model (Motawa and Carter, 2013; Tse et al., 2005) to account for the wide range of possible configurations of that modelled building prior to simulation. There are also problems encountered when the data sources to populate these interfaces are not comprehensive enough to give an accurate depiction of the building (Gökçe and Gökçe, 2014). In EPM software, the user has control over all aspects of this configuration; for example, the number of occupants in each space and their pattern of occupancy can be configured for each individual simulated space, allowing for much more accurate simulation.

Non-integrated methods of sharing models and building meta-data between BIM and

EPM tools have been created, making use of the IFC format as well as the more building energy performance related Green Building Extensible Mark-up Language (gbXML) format. Both have the capacity to store geometry, construction materials and basic heating, cooling and ventilation values providing input to a predictive model, but each is limited by the capability of the tools utilising them in recording that information in the appropriate way for extraction and interpretation later on (Korhonen and Laine, 2008).

Prior to widespread adoption of BIM, Bazjanac and Maile (2004) demonstrated a method of importing building geometry and HVAC systems from building and system modelling tools into EnergyPlus (an EPM software package). This was further developed by Kim et al. (2012) who addressed the complexity of interoperability between BIM tools, developing a converter between the IFC and an Input Data File (IDF) (used by the EnergyPlus EPM software) to maintain data integrity in this transfer. However, as these functionalities have been developed, there remains a barrier to full interoperability between BIM for building design and EPM for performance simulation for the reason given by Maile et al. (2007), that modelling tools each have their own purpose, and where modelling for one purpose does not make that model suitable for another (Choi and Kim, 2011). For example, an architectural model used for visualisation of a proposed development would not be suitable for EPM due to the need for high tolerances and zoning to provide an appropriate simulation environment. These differences mean that interoperability between the two modelling systems requires iterative attempts (Miller, 2010; Korhonen and Laine, 2008), and interim tools such as those created by Kim et al. (2012) and Bazjanac and Maile (2004) must be used in addition to manual error correction before interpretation in the receiving environment.

2.2.2 During building handover

The handover of a building upon completion begins the longest stage in its life-cycle, fulfilling its purpose in providing a suitable environment for the purpose of its construction (Fallon et al., 2007). Utilisation of BIM to enhance this handover process by using it as an information repository is seen by Gnanarednam and Jayasena (2013), BIFM (2012), and Clayton et al. (2009) to have massive potential for more effective Facilities Management (FM), through greater access to materials relevant to the operation of the building.

Design intent vs. implementation

According to Neumann and Jacob (2010), building operators often make decisions regarding the operation and maintenance of the building they are responsible for, based on intuition and experience. A consequence of this may be that these decisions may not be suitable for the building being managed (Bennett et al., 2012; Pathirage et al., 2008; Amaratunga and Baldry, 2002). The availability of quantifiable performance metrics and HVAC systems data enables informed decision-making, reducing inefficiency and improving overall building performance (Pérez-Lombard et al., 2008). However, as suggested by Jylhä and Suvanto (2015), the amount of information is less important than accessibility to the right information, to support better decision making for building energy performance optimisation.

Utilisation of BIM as a 'single source of truth' in which design intent can be stored

could add justification to *why* a building should be operated in a particular way, not just specifying *how* it should be operated. To support this, building handover is beginning to be managed as a transitional process (Demanuele et al., 2010), with initiatives such as Soft Landings (Cabinet Office, 2012) facilitating this. The soft-landings initiative (BSRIA and Usable Buildings Trust, 2008) recently adopted by UK government involves clients in the initial and ongoing Continuous Commissioning (CC) processes for the building they occupy. Through taking the time to familiarise occupants with the building's they inhabit, building energy performance can be improved through more effective operations management (Pérez-Lombard et al., 2008), where reduction in operating cost can outweigh the cost of implementing additional schemes (Hampton et al., 2006).

Information handover

Information handover is the underlying mechanism enabling FM staff the ability to interact with the building and systems therin. Implementation of BIM to facilitate far more extensive information transfer than previously employed is one goal of the BIM Task Group (2011), partially through methods such as the Construction Operations Building information exchange (COBie) data-drops (BIM Task Group, 2012). COBie, developed by East (2007), is a framework for the recording, development and handover of building information facilitated by BIM (Anderson et al., 2012) to improve the effectiveness of that handover and make the relevant information immediately accessible to the building operators. Accessibility of information within this format is vital, and given the scope of data combined in this spreadsheet format this can be both a benefit and detriment to effective utilisation by FM. Work by Kohlhase (2013), Thorne and Ball (2005), and Chen and Chan (2000) found that the inordinate detail contained in such a format may hinder retrieval of specific information, and its interpretability. Whyte et al. (2010) found that while cost benefits of implementation were not clear, there was a perceived tangible benefit to be found in handover of models containing such FM accessible information, with Way and Bordass (2005) suggesting that investment in improved exchange of design intent is less than the gains made from the lessons learned.

COBie is not fully representative of information stored in a BIM environment, as it is a spreadsheet-based environment containing a subset of the information stored in a full BIM (specifically a subset of information contained within an IFC file from which a COBie spreadsheet can be generated) in which descriptive building asset and equipment data can be stored. Ongoing work in preparing data for exchange following a standardised format is being addressed by Kalin and Weygant (2013) in Specifiers' Properties information exchange (SPie) and being incrementally adopted in the UK as Product Data Templates (PDTs) by CIBSE (2016).

Currently within the UK, the method of specifying information handover to the client at project outset, during which responsibilities and extend of information stored within a BIM environment, is detailed is through the Employer's Information Requirements (EIR). Within this document the following specifications are given:

– Software platforms used for generation of models;
– Information exchange formats (including naming conventions and references coordinates for coordination);
– Extent of detail for modelled objects;

– Stakeholder roles and responsibilities;

– Coordination and collaboration processes (including exchange, coordination and review schedules);

– Delivery plan until project completion;

– Defined project deliverables; and

– Strategic purpose, justifying the preceding points and their eventual utilisation.

The content within the EIR aims to clarify the extent of information delivered upon project completion, with its implementation part of BSI (2013c). Details to be specified within the EIR are subject to interpretation however, and consideration of project specific requirements is required where necessary. For example, building performance information is not part of a standard BIM deliverables package and would not be included as standard, instead left to the FM handover information.

Building commissioning

During handover, the building undergoes commissioning and testing of the equipment required for climate control. This consists of a comprehensive examination and Heating, Ventilation, Air-Conditioning and Refrigeration (HVAC&R) systems and their operation, as well as coordination of data describing the building's fabric, equipment and maintenance procedures (NIBS, 2015). The strict definition of commissioning is that it ensures all building operations systems interact in accordance with the design intent (Djuric and Novakovic, 2009). According to Wang et al. (2013) and Djuric and Novakovic (2009), occupant interaction is paramount within this process due to its importance in relation to the systems and schedule by which the building is operated. The occupant fundamentally determines the level of servicing required in maintaining an acceptable indoor environment, and is the end-user of energy consumed by the building (through small power, lighting and heating). Understanding how these interactions take place, and where inefficiency is being introduced would greatly reduce the performance gap discussed previously (Menezes et al., 2012; Visier et al., 2008).

In addition to the occupant's impact on building energy consumption, several studies highlight the potential energy savings of between 15-20% from correct installation and commissioning (Pisello et al., 2012; U.S. Department of Energy et al., 2012; Roth et al., 2002). Including retrofit of older buildings, Mills et al. (2004) recognised commissioning as one of the most cost-effective ways of improving energy efficiency in commercial buildings, with 1-2 year paybacks using basic CC principles of monitoring performance, involving the occupant, measuring response to changes implemented (Teicholz, 2013; Claridge et al., 2000). Use of design EPM models to provide an exemplar commissioned building based on its expected level of performance (similar to application of BIM to produce a COBie dataset) have been demonstrated by Stenzel et al. (2014); though, integration within a BIM is yet to be commonplace, as described in Section 2.2.3.

2.2.3 During building operation

During use, the data generated in design can be re-purposed, providing the building operator the ability to understand not just how the building operates, but why it was

designed to operate in that manner (Wilkinson, 1999). This understanding can lead to better management of that buildings performance, and reduced energy consumption (Hong et al., 2015; Brown and Cole, 2009; Haldi and Robinson, 2008).

The other side of the performance gap as described in Section 2.1.2 is the operational phase of a building's life-cycle. Here, numerous factors impact the expected performance of a building such as changes in use, unexpected occupant behaviour (Wang et al., 2012), reduction in equipment performance over time (Golabchi et al., 2013; Douglas, 1996) and changes to that equipment as a result (Homer et al., 1997). Monitoring a building's ongoing performance provides a means of indicating where inefficiencies are present in its operational strategy, identifying issues impacting the energy consumed and occupant comfort (Federspiel and Villafana, 2003).

BMS implementation

Measured energy performance data is a by-product of the implementation of a Building Management System (BMS) for the scheduling and control of building systems. Use of these measurements to direct changes in operation have been shown by Granderson et al. (2011) to reduce fuel and energy consumption by up to 30%. The primary purpose of a BMS is to control the multiple HVAC systems in place, keeping a building conditioned to the level expected by its occupants. Additionally, it acts as an indicator of problems with that conditioning and equipment (Ulickey et al., 2010). Fault detection and equipment upkeep require a system of monitoring building conditioning equipment to ensure optimal performance; however, a BMS is generally only used to indicate problems, not to predict them or make changes to avoid them (Costa et al., 2013). Improper use, installation or maintenance of BMSs have been identified as a key aspect impacting building energy performance (Painter et al., 2012). In addition to proper configuration, selection of the type of information to be monitored must be made based on the requirements of the user (Azar and Menassa, 2014), the complexity of the spaces being monitored (Haves et al., 2001), and the purpose of monitoring these criteria (Hensen and Lamberts, 2011).

The automation of building management has been demonstrated by Mathews et al. (2002) to improve overall performance, although Buckman et al. (2014) explain further that implementation without consideration of impact is necessary for this to be effective in improving building energy performance. Automated optimisation of operations have been found by Marinakis et al. (2013) to significantly reduce servicing loads through actively monitored systems, with scope for such a tool also identified by Yin (2010) and Baumann (2005), who suggest that monitoring systems and management tools could be more cost effective than external intervention through performance auditing. The technologies available to support integration of tools are continuously developing, with communications protocols for specific building performance monitoring applications (such as BACnet, KNX, LonTalk and Modbus) capable of being interpreted by multiple different BMSs; however, communication with non BMS platforms such as BIM has yet to be investigated except via proxy interfaces (Costa et al., 2013; Wetter, 2010).

BIM integration with BEM

Integration of EPM with BIM is where the majority of research around design stage application of BIM to enhance performance design has been focussed in recent years (Dowsett and Harty, 2013; Sinha et al., 2013; Aziz et al., 2012; Sanguinetti et al., 2012; Aksamija et al., 2011; Welle et al., 2011; Azhar et al., 2009; Schlueter and Thesseling, 2009; Krygiel and Nies, 2008) perhaps due to the leg between design, handover and operation of buildings; however, potential benefits are now being explored in the use of BIM during the operational phase of the building's life-cycle (Love et al., 2015). Cahill et al. (2012) demonstrates use of the IFC format (the common exchange format used for interoperability of BIM data between various modelling tools) to attribute static data values as part of a larger performance monitoring network, while efforts to develop co-simulation tools linked monitored data with concurrent simulations to give an accurate representation of actual building energy consumption (Moon et al., 2013; Wetter, 2010). From this, performance improvements could be identified and the data managed using the IFC schema. These novel uses show that accessibility to information generated both during design and operation and the links between these represent a distinct opportunity to better understand the building's we occupy, with research by Cahill et al. (2012) suggesting BIM as the centrepiece to that opportunity.

Automation of BEM using BIM is a narrow field of research, with its predominant focus on application to Fault Detection and Diagnosis (FDD) to identify issues in performance. This has been demonstrated by Dong et al. (2014) in conjunction with a BIM based database, and in the framework developed by Pang et al. (2012) to indicate potential faults as they occur. Automating the creation of these relationships between databases is a challenge, given the complexity and variability of buildings and their systems, but is an important topic to address in linking BIM and BEM (Katipamula and Brambley, 2005).

Curry et al. (2013) and Curry et al. (2012) investigated the link between operational decision making and BIM as a CDE, using monitored performance data in conjunction with an existing BIM. This provided an interface, but little analysis of this data to support operational decision making. One example showing development towards this ambitious goal is the Building Controls Virtual Test Bed (BCVTB) developed by Wetter (2010), building on work by Bazjanac and Maile (2004) and further implemented by Moon et al. (2013) and Pang et al. (2012), which linked BMS and energy analysis for parallel performance simulation using IFC as a framework by which that information is modelled. These studies, while demonstrating the potential for BIM to support BEM, are all implemented in situations where total control was available of the systems in place (university buildings and monitoring of specific aspects of performance) to provide information to the platforms used. As such, the applicability of their findings to the wider industry, and buildings not under unitary management brings forth several new challenges (analogous to issues of generalisability (Lee and Baskerville, 2003) and reproducibility in other research areas (Anda et al., 2008)). These include the access to monitored data, skills of the FM team in implementing new systems and processes and scope of the tools provided to effectively portray a building's performance with minimal user input.

Despite the research referenced, there is not definitive proof of the potential benefits BIM may have on in-use BEM, particularly within industry. This may be due in part to the novelty of this research currently, and the non-uniformity of buildings and metrics to which an individual building can be measured, impacting uptake of the available examples.

Studies by McGraw Hill Construction (2014) and McGraw Hill Construction (2010a) demonstrate the perception of value BIM adds to building projects (during both design and operation); however, quantifiable performance benefits are more difficult to estimate (Dowsett and Harty, 2013; Love et al., 2013; Barlish and Sullivan, 2012). Similarly, cost benefits can be estimated, yet resources for these proving quantifiable benefits of BIM are rare (Giel and Issa, 2013) and as buildings are constantly changing, comparison with themselves at an earlier point in time and other similar buildings without such interventions may not be entirely accurate.

POE and the impact BIM may have

A review of energy performance optimisation during building operation would not be complete without Post-Occupancy Evaluation (POE). POE is the intervention during a building lifetime where its performance is audited, analysed and improved upon through comprehensive collection of its quantifiable performance data (from equipment energy consumption), and qualitative data from occupants (their experiences of the building such as level of comfort from temperature, noise and aesthetics). There have been several attempts made to more effectively facilitate POE using BIM, such as that by Motawa and Corrigan (2012) and Ozturk et al. (2012) who demonstrated data collection around a BIM environment, though most research in this area does not propose use of BIM to support this process (Yu et al., 2011; Haldi and Robinson, 2008; Clevenger and Haymaker, 2006). One such example of a novel use of BIM interacting with occupants during building operation is given by Shen et al. (2012), who demonstrated a method of mapping occupant location to BIM as a framework, which could potentially be used in conjunction with other monitoring methods to better understand energy consumption from respective occupant activities. Extensive POE studies have been conducted in the past (Bordass et al., 1999), providing evidence of the performance gap, though use of BIM is still limited to attribution of collected data and providing a framework for the management of that data (Ozturk et al., 2012).

Together, the above topics present the state of BIM currently throughout building energy performance design and management, each related to the scope of this research.

2.3   Gaps in the literature

A number of gaps were identified during the review of available literature, demonstrating the need for the research presented here. BIM research applied towards the improvement of energy performance in buildings is primarily focussed on design aspects, highlighting the potential for interoperability between design tools and reduction in the time taken to explore various options for optimisation (Matthews et al., 2015; Dowsett and Harty, 2013). As design benefits from the implementation of BIM are widely recognised, examples of the adoption of BIM supported tools and systems in building operation are far fewer, mainly due to the lack of uptake of untested processes by building operators (Bennett et al., 2012; BIFM, 2012; Pathirage et al., 2008). Limited examples, such as those by Codinhoto et al. (2013), demonstrate the fiscal benefits use of BIM has for building operators, research has focussed on areas where this benefit has been measured or estimated with more in-depth investigation (Giel and Issa, 2013; Barlish and Sullivan, 2012; Bryde et al., 2012;

Neelamkavil and Ahamed, 2012; Succar et al., 2012; Becerik-Gerber and Rice, 2010; Gallaher et al., 2004).

BIM research for interoperability with building energy modelling and management focuses on the use of exchange formats to enable cross-platform data exchange (Ham and Golparvar-Fard, 2015; Dhillon et al., 2014; Aziz et al., 2012; Hitchcock and Wong, 2011; Bazjanac, 2008). Until now, the IFC standard has been used as an extensible format for meta-data attribution, but its use for the storage and exchange of building performance information (or more specifically, performance information that changes over time) is yet to be examined. This additional functionality could integrate in-use performance management of a building with a representative model to truly represent a CDE in which holistic performance could be managed.

The implementation of any new technology or process in the AEC industry takes time (Gerrish et al., 2014; Gu and London, 2010; Nikas et al., 2007). When addressing such a wide audience (including occupants, FM, building owners and building designers) there must be consideration of the social and technological aspects of managing a building's performance (Gerrish et al., 2016c). Existing work by Kumaraswamy et al. (2014) and Costa et al. (2013) looked at this from both a BIM and non-BIM perspective of performance visualisation, showing that performance interpretation aids such as BIM would help improve occupant understanding of building energy performance. BIM is yet to be brought into this area, and provides a comprehensive source of design information to which that performance data could be linked (Gerrish et al., 2015).

The studies examined here all share a common feature. Their applicability to the wider AEC industry is evident in each study, demonstrating improved management of a building in-use energy performance. However, these applications are theoretical given the range of buildings and factors required to enable implementation of each. Data describing a building's changing performance is becoming more accessible (Wei and Li, 2011), but the platforms to investigate this information are limited to proprietary interfaces and tools such as that created by LBNL (2015). There is also limited guidance for non-engineers to make sense of their monitored performance data compounded by building owners and operators not being made aware of the disparity between operational and capital expenditure and the opportunities for improvement particularity during the latter, further exemplifying a non-technological issue to implementing BIM for performance improvement purposes. Concurrently, data is becoming accessible from BIM upon handover of the building, suggesting the potential for use to be made of these two data sources in conjunction with each other.

2.4 Summary

This chapter reviewed the available literature surrounding use of BIM as a tool supporting the performance management of non-domestic buildings, explaining its relationship with progressive stages of the building's life-cycle and giving context to the research problem. A holistic approach is necessary given the far-reaching impact BIM is having on all aspects of building design and operation; however, focus was given to the key areas of information development and exchange, performance management through building operation, and methods of using that data to better inform efficient building operation.

Gaps in the literature are presented as: a lack of interoperability between design tools; perceived rather than measured benefits from BIM application; limited examples of BIM for building performance data storage and exploration; and the limited applicability of existing proprietary interfaces outside academia to utilise this data without extensive skills in the development and application of such tools. The research methodology is presented in Chapter 3.

3 Research methodology

This chapter presents the methodology adopted in this research describing each task, its applied methodology and the justification for its application.

3.1 Introduction

Research is the systematic investigation in a field of knowledge using appropriate methods to establish facts, solve problems or simply to increase the body of knowledge in that particular field (OECD, 2015). The aim summarised in Section 1.5 and defined as objectives and tasks in Section 1.6 are approached using various methodological considerations. Where possible, research progressed linearly, following an expected path with logical steps taken to further understanding of a subject and output findings. In some portions of this research this path became less suited to the direction it was taking and more suitable methodologies were adopted on an ad-hoc basis (Fellows and Liu, 2015).

3.2 Research perspectives

Defining the methodology or methodologies to be implemented for effective, valid and reliable research output requires consideration of its objectives and tasks undertaken therein, relevant to the constraints of that research. Following the example set by Sheriff (2011) for research undertaken as part of an EngD, the perspectives of research within which the methods described here may be categorised. The specific interpretations of each style applied to the adopted methods are outlined as follows:

Application
   Research may be split between two distinct types, pure and applied. Pure research is an abstract investigation of theories or hypotheses that are not currently applicable to practical scenarios both current and foreseen, whereas applied research is the use of existing methodologies on defined problems to address a particular question, with more immediately practical application (Kumar, 2011). This, by definition, is less theoretical than pure research as it focusses on the research problem and not just the research method.

Paradigms
   Fellows and Liu (2015) suggest two paradigms through which research can be interpreted (although each methodological interpretation in this section may also be called a paradigm). A positivist paradigm is one of an objective reality in

which deductive scientific methods are applied to discover patterns and regularities (Denscombe, 1998). An interpretivist paradigm supposes that the act of research itself impacts the subject, creating a subjective interpretation of the research outcome (Weber, 2004).

Objectives

Robson (2013) and Maxwell (2012) outline four types of research, as defined by their objectives. 'Exploratory' studies explore something and ask questions about it; 'descriptive' studies provide a detailed account of an occurrence to portray relations between examined subjects; 'explanatory' studies explain why and how something happens, identifying the underlying reasons; and 'interpretive' studies explore the experience of a subject and their views on that experience (Gray, 2009).

Inquiry

Inquiry is the mode of research that understands that the solution to an initial problem leads to further questions (Cresswell, 2008). This philosophy is most relevant to the research undertaken here, as an exploration of a topic is most like an inquiry where initial questions are asked in separate, yet related topics (Section 1.3). Upon generating findings from that initial question, heuristic investigation in those topics following challenges identified in the first investigation are then addressed (Section 1.6), as described by Gray (2009, p. 33).

Using the research perspectives outlined here, the methods of research undertaken may also be categorised broadly as either qualitative or quantitative, of which definitions are given by Cresswell (2008) as "*exploring and understanding the meaning individuals or groups ascribe to a social or human problem*" and "*testing objective theories by examining the relationship among variables . . . [which] in turn can be measured*" respectively. The subject of Building Information Modelling (BIM) is one impacting almost all aspects of the Architecture, Engineering and Construction (AEC) industry, and therefore a mixture of both qualitative and quantitative research is necessary to examine both the potential for BIM as both technological change and procedural or process-based, impacting those working with it. This is known as 'mixed methods research' (Cresswell, 2008), where multiple sources of data are used in conjunction with various data-gathering techniques to increase the credibility of research outcomes. The phenomena explored within the research presented constitutes a pragmatic perspective, not limiting scope or outcome through focus on a single method and opening the subjects review to multiple influencers identifiable through consideration of both quantitative and qualitative sources of information (Onwuegbuzle and Leech, 2005).

3.3 Applied research perspectives

The aim of this research was to explore how BIM could be used to manage the performance of non-domestic buildings, which by definition makes it 'applied' rather than 'pure' in its investigation. The potential for this work to be built upon as pure research (using the methods chosen in non-applied and theoretical ways) is possible, due to the changing nature of BIM in relation to building energy design and management; however, this is unlikely given the generally direct applicability of research within the AEC industry

(Becher and Trowler, 2001). In areas where research is exploratory it may be beneficial to consider both pure and applied forms, where the theoretical potential for information exchange and interpretation is explored, but not applied given the limitations discovered upon investigation.

Objective 1 aimed to provide a review of the current state-of-the-art in BIM, in which a 'descriptive' methodology was appropriate (Task 1, Section 4.1). Establishing the BIM capability within the sponsoring organisation (Task 2, Section 4.2) required an interpretive and exploratory paradigm, using interviews to record subject experiences as-well as distinguishing reasons behind these responses. Definition of a standard for information sharing between BIM and Energy Performance Modelling (EPM) environments (Task 3, Section 4.3) was applied to projects undertaken by the industry sponsor, from the perspective of exploratory inquiry, forming a large part of this feeding into later research direction.

Objective 2 and Objective 3 were predominantly exploratory, using an inquiry-based approach to assess means of managing building performance through BIM (Task 5, Section 4.5), except for the creation of representative models, which were more descriptive and interpretive by nature of data aggregation and amalgamation (Task 4, Section 4.4). Analysis of data from the in-use building (Task 6, Section 4.6) required assessment of quantified data, to which descriptive study was applied using a positivist paradigm (due to the fixed historic data not changing throughout); however, given the amount of processing required to interpret this data it may also be considered an interpretivist paradigm.

The generation of a method of BIM-supported building energy began as pure research, exploring the subject area and potential methods, but developed into applied descriptive research following application to a case-study building (Task 7, Section 4.7). The critical evaluation (Task 8, Section 4.8) of this in Objective 4 and the research as a whole constitutes a critical descriptive methodology.

3.4   Methodological limitations

Justification for this research stems from the potential of BIM to provide a means for building operators to make use of the information generated during design, to assist with the management of that buildings performance. This suggests a mixture of both qualitative and quantitative methods is appropriate as adoption of new technologies for optimising systems and performance, and implementation of these requires understanding of those systems. For example, operational performance of a building relies on multiple factors, notably the efficiency of quantifiable measured plant equipment and the qualitatively differing methods of operation by Facilities Management (FM) and building occupants of those systems.

The following factors specify what was considered in the definition of appropriate holistic and ad-hoc methodologies:

- The research questions posed at project outset were open-ended. As the expected outcome was unknown, a reactive approach was required during early stages to respond to findings and developments in the fields as they occurred;
- The human element of technology and process adoption featured prominently in

early stages of research (Section 1.5.1), necessitating an understanding of how users generate and interact with information in and around the Common Data Environment (CDE);

– The body of knowledge around the capabilities of BIM in conjunction with development around building energy performance optimisation as it was at project outset was extensive, and constantly growing. A meta-analysis of publications available from Scopus (2016), show that publication rate in this area has grown significantly in past years (with rate of publication tripling between 2011 and 2015); and

– The building around which research took place was not developed using BIM systems and processes by the research sponsor. As such, access to information pertinent to the use of design-based BIM information for use in operational performance was limited.

Resources available to the Research Engineer (RE) throughout research included:

– Supervision from academic supervisors, access to the university's library and journal subscriptions;

– Supervision from industrial supervisors, access to training and projects both completed and under development; and

– Industry bodies with relevant expertise and knowledge, through membership of professional organisations.

Constraints applied to the research during tasks carried out, requirements of the research programme and responsibilities within the sponsoring organisation included:

– Limited access to external industry information beyond control of the sponsoring organisation (for example, Building Management System (BMS) records, billable services consumption records and FM activities information);

– Requirement for a number of peer-reviewed publications; and

– Input into ongoing project development, and application of the skills developed during research to live projects.

3.5 Selected research methodologies

Within each of the objectives, the specific methodologies used are described and justified below, relating each to the appropriate methods implemented to reach an outcome from which research could then progress.

3.5.1 Objective 1

In Objective 1 (Section 1.5.1) the exploration of the research topic was conducted. This included current industry capabilities in the subjects of building energy performance evaluation and management, the adoption of BIM tools and processes, and the relation between these areas during both design and operation.

Task 1

The literature review consisted of an extensive search of related literature around the fields of BIM and Building Energy Management (BEM). Common themes between these topics indicated the need for triangulation of a wide range of methods to explore the topic to the extent required to advance one particular aspect. Output from this task is included in Chapter 2.

Task 2

Information obtained from the literature review showed a lack of development in the interoperability between EPM and BIM, though efforts were being made in this area to improve. To gain a greater understanding of the current Knowledge Management (KM) capabilities of the sponsoring organisations implementation of BIM, 30-minute semi-structured phone interviews to gather in-depth experiential perspectives (Sturges and Hanrahan, 2004) with six members of the distinct disciplines within BuroHappold. These were a qualitative method of gathering information about the industry sponsor and guided the topic of conversation using open-ended questions to direct discussion in a particular area (Bernard, 1988).

This work would later go on to form the basis for an organisation-wide survey, implemented using a web-based platform which was used to determine a strategy for comprehensive BIM adoption across all regions and disciplines. The findings from this study, applicable to other multidisciplinary engineering consultancies adopting BIM was published as a paper in Appendix A (Gerrish et al., 2014) and is summarised in Section 4.2.

Task 3

The means through which information was developed and shared between the mechanical engineer and building physicist during design development was examined through project and process review. Quantification and categorisation of information developed at distinct stages was aligned to a development and exchange framework around which information could be shared between these disciplines to support more effective information sharing. Emphasis was placed on the utilisation of existing technologies, and later with the advent of new modelling capabilities, the opportunity to test this framework was made available using tools such as Dynamo (Autodesk, 2015a). The methods here consisted primarily of reviewing existing processes, and streamlining these to optimise information development and exchange, reducing rework and increasing transparency in data development. A systems and actor perspective was used to generate this framework, as outlined by Arbnor and Bjerke (2009). This work is detailed in Appendix C (Gerrish et al., 2015) and summarised in Section 4.3.

3.5.2 Objective 2

Objective 2 (Section 1.5.2) began work focussing on a case-study building, making sense of information generated during design and measured through ongoing operation. All activities during this stage were conducted concurrently with the amalgamation of

existing models, the creation of new representative models and interpretation of obtained data.

Task 4

Outputs from this task included a partial as-built BIM using Revit (Autodesk, 2015c) of the case-study building, incorporating performance characteristics in conjunction with a representative energy performance model built using Integrated Environmental Solutions – Virtual Environment (IES-VE) (Integrated Environmental Solutions, 2016). This required critical review of engineering design documentation and Operations and Maintenance (O&M) manuals; using model development principles described by Raftery et al. (2011). These provided the basis for further research in the following tasks, and datasets describing design performance for connection with operational performance data in Tasks 7 and 8. The actions taken in Task 4 are summarised in Section 4.4.

Task 5

Investigation into attribution of output from an EPM or BMS record into a BIM environment was undertaken to explore the potential for Industry Foundation Class (IFC) as a carrier format for this type of information. The method used here critically examined the IFC format using 'grey-box' testing methods (Li et al., 2008) of input application and output analysis, to determine the feasibility of using IFC to store time-series performance related information. Findings from this are described in Appendix B (Gerrish et al., 2016c) and detailed in Section 4.5.

3.5.3   Objective 3

In Objective 3, the development of a method to manage a building's energy performance using BIM was approached, using an exploratory inquiry paradigm, in addition to a more descriptive perspective of interpreting monitored building energy performance data.

Task 6

Collection of the logged data describing aspects of the case-study buildings operational performance used an in-situ BMS. Exploratory analysis (Aigner et al., 2007) and decomposition of logged data determined particular aspect performances derived from sub-metered spatial and systems performance data. The method developed to distinguish spurious readings used Winsorisation in conjunction with user input (Section 4.6.1), initially identifying the data being evaluated, understanding what it describes to ascertain its likely format, then identifying errors for accommodation prior to analysis*. Additional development of specific analysis functionality to perform trend analysis of large datasets was then approached, outlining under-performing spaces within a comparable set in a building. This work is described fully in Appendix D (Gerrish et al., 2016b), with the process and findings outlined in Section 4.6.

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*A brief introduction to the programming language and packages used throughout the development of the processes described here is included in Appendix F.

Task 7

Attribution of designed performance data to the BIM used Revit and its extensible parameter creation capabilities to create a comprehensive dataset describing as-designed building performance. A pragmatic multi-method approach was used to develop a means through which building performance information in a BIM environment could be linked to monitored 'real-world' data. Prototyping was used to develop a method for linking a BIM model with BMS output, requiring incremental development within each specific function created. Based on the concept of 'throwaway prototyping' (Crinnion, 1992), a functioning method was developed to achieve this link. The dynamic system's development method (DSDM Consortium, 2014) was considered for application to the methods development, but given the RE's skills in this area, and the need to develop the concept quickly, throwaway prototyping was the method used. However, the process described by DSDM Consortium (2014) of identifying a prototype, planning its functionality, creating and reviewing it was followed. This is summarised in Section 4.7, detailing the challenges currently present interoperating between BIM and building performance management through an experiential process (Roth, 2012).

3.5.4 Objective 4

Objective 4 constituted the application and evaluation of the prototype method, summarising the efforts to link BIM with building energy performance management. Findings from the entire research process culminate in a report on the potential for development in this area with guidance given to implement a suitable framework to achieve such a goal.

Task 8

The implementation phase of the prototype method constituted an evaluation of potential, rather than direct interface between the case-study buildings BMS and information in a BIM environment. Interpretation of its utility was made through feedback from stakeholders in the building's design, handover and operations processes, and use of the visualisations output from the developed analysis tools, indicating opportunities for improvement in both the method and the building's operation. Demonstration of the developed method for linking design and operational data to those stakeholders, followed by semi-structured interviews gathering feedback and wider contextual issues (such as designer and operator experiences in using BIM environments and the impact this is having on their processes) was used to evaluate its potential and indicate wider issues in adoption of this or similar methods. A critical review of the research processes leading to this task, and potential applicability is detailed in Appendix E (Gerrish et al., 2017b), and summarised in Section 4.8.

3.6 Summary

The relationship between each of the philosophical research paradigms reviewed in Section 3.2 and the tasks constituting this research is shown in Table 3.1, constituting a

wider research philosophy of pragmatism, accounting for multiple-methods contributing to a holistic research programme around the subjects explored.

Table 3.1: Philosophical research paradigms applied to specific tasks defined within this research

	Research paradigm	Applied methodology
Objective 1		
Task 1	Descriptive	Literature review
Task 2	Interpretive, exploratory	Semi-structured interview, questionnaire
Task 3	Interpretivist, exploratory, inquiry	Multiple-method, internal presentation
Objective 2		
Task 4	Descriptive, interpretivist	Document amalgamation
Task 5	Exploratory, inquiry	Interoperability testing
Objective 3		
Task 6	Positivist/interpretivist, descriptive	Data collection, time-series visualisation
Task 7	Applied, explanatory, descriptive	Parametric visualisation, application & testing
Objective 4		
Task 8	Interpretivist, interpretive, descriptive	Multiple-method, semi-structured interview, observation & critique

Given the scope of the wider subject domain, and need for focus around the specific topics identified in Chapter 2, clear definition of the methodologies to be applied at research commencement was required. However, the concurrent evolution of the subject area and exploration of these meant flexibility in methods adopted was also necessary. More details around the application of methods described here, and the research outcomes from each are included in Chapter 4.

4 Research undertaken and results

This chapter presents the research undertaken as outlined in Chapter 1, using the methods described in Chapter 3. The research pathway is narrated, with key results highlighted in context with the research undertaken.

4.1 Preparation and subject familiarisation

The earliest stages of this research formed the definition and development of the overall research objective, through in-depth review of the related literature around Building Information Modelling (BIM) in the context of building energy performance. Preliminary studies included investigation into the industry sponsor, aiming to understand its structure, culture, operations and needs later feeding into the review in Section 4.2. This action outlined the competency and capability of the research sponsor in its implementation of BIM throughout building design and energy performance optimisation, and provided a basis for targeted development. In addition to these introductory actions, professional development courses were attended to improve the Research Engineers (REs) skills in areas ranging from specialist performance analysis tools, visual programming and interpersonal skills training, providing valuable resources to the RE's technical and managerial competencies.

The following sections detail each objective and the research undertaken therein, contributing to wider knowledge on how BIM could be used to manage operational building energy performance.

Objective 1: Subject exploration and sponsoring organisation context

The first objective involved a detailed exploration of the current state-of-the-art in BIM. Task 1 comprised a literature review defining BIM and its related subjects within energy performance management during design and operation (Chapter 2); examining the component subjects of BIM and building energy performance design and optimisation to identify gaps in research and application. The findings from this established that despite recognition of the benefits that the application of BIM to life-cycle building performance management would have, its implementation has been limited (Göçer et al., 2015; Yalcinkaya and Singh, 2015; Costa et al., 2013; Mäkeläinen et al., 2012; Mihindu and Arayici, 2008). This is partially due to constraints of information accessibility and availability during design and operation (Wei and Li, 2011); suitability due to the errors in recording and handling data during design and operation (de Wilde, 2014); and user capability (BIFM, 2012) limiting application of complex information management systems without expert intervention (detailed in Section 2.3).

Findings from this review are presented in Chapter 2. Alongside these findings, a readiness and capability study of the industry sponsor was undertaken to investigate how industry wide findings such as those demonstrated by Azhar (2011) were experienced on a smaller scale, and provide the basis for further development tailored to the research sponsor.

4.2   Task 2: Review the BIM capabilities and adoption strategy of BuroHappold

As an introduction to the industry sponsor and means of identifying current BIM information exchange processes, a series of six semi-structured interviews were carried out with representatives from major disciplines present within BuroHappold. Additionally, an assessment of BIM incorporated projects was made, each ranked each in terms of their BIM capability maturity as defined in BSI (2013c) and BIM Task Group (2011) in the Bew-Richards model due to its focus on BIM implementation within the UK. This portion of research was is detailed in Appendix A (Gerrish et al., 2014), with additional work completed afterwards applied to the organisation globally to assess employee perceptions of BIM and influence implementation strategy.

4.2.1   Project review

A project-based survey examined four recent projects in which the structural and building services disciplines were extensively involved, using BIM as a primary mechanism for information development and exchange. Of these, three were primarily structures-based and one building services-based. Given the early stages of BIM adoption within BuroHappold at this time, sourcing projects in which all information was managed using BIM meant limited projects were available for analysis. Each was rated according to its capability/maturity using the NIBS Capability Maturity Model (2007, pp. 75–82)

for project aspect maturity, and distinction between organisation and project capability (inclusive of external stakeholders). The NIBS model was used in favour of the Bew-Richards model due to its focus on project-specific maturity rather than individual or organisational capability and maturity.

The structures-based projects scored consistently high in areas of geometric modelling, interoperability and exchange between tools, whereas building services were less capable in these areas. More specifically, in the development and collaboration between sub-disciplines within building services where purpose specific modelling precludes holistic modelling in an integrated environment. Additionally, there was disparity between organisation-based capability and project-based capability, where collaboration with external design stakeholders and contractors who were not yet capable of handling information developed using BIM authoring tools, reduced capability (Gerrish et al., 2014).

4.2.2 Discipline interviews

Semi-structured interviews were used to examine how the industry sponsor was adopting BIM tools and processes, identifying how different disciplines were approaching implementation, and barriers to its effective use. The NIBS Capability Maturity Model (2007) was once again used as a framework defining subjects, about which the interviews focussed (further details of this process are given in Appendix G.1); grouping the scored areas for maturity assessment into thematic categories incorporating the technical and methodological elements of BIM implementation and its impacts. Findings from the initial project review steered questioning around the following categories, delineating capability maturity of the discipline groups and the individuals therein, and the wider knowledge base contributing to more effective work-flows through common methods and procedures for sharing information:

– Collaboration;
– Information transfer;
– Standards and interoperability;
– Knowledge transfer; and
– Future capabilities.

Interviews were undertaken with representatives from each major discipline within the industry sponsor of structural engineering, building services engineering, building physics, IT (providing the infrastructure for BIM implementation) and management (overseeing coordination between these disciplines). Each interviewee was chosen due to their responsibility implementing BIM in their representatives disciplines (Table 4.1), and while these do not represent all potential disciplines within the research sponsor, the conversations aimed to elicit perceptual BIM capabilities from those directly involved in its adoption. Interviews were recorded and transcribed to enable semantic categorisation into the categories specified, and attribute a level of maturity using inductive reasoning that could be used to quantify discipline specific performance. Topics of discussion used as starting points for the semi-structured interviews are described in full in Appendix G.1, with thematic categorisations for each theme indicated.

Findings from the interviews indicated that concurrent adoption strategies were not in-place throughout the organisation and between disciplines, and that the silo-mentality

Table 4.1: Semi-structured interview respondent response categorisation

Interviewee	Job title	Collaboration	Information transfer	Standards & interoperability	Knowledge transfer	Future capabilities
A	Senior structural technician	★	★	★	★	
B	Lead systems analyst (IT)	★	★	★		★
C	Computer Aided Design (CAD) & BIM manager (building services)	★	★	★		
D	Senior building services technician	★	★	★	★	★
E	Associate director of sustainability (building physics)	★	★		★	★
F	Project principal (management)	★	★	★		★

identified by Gal et al. (2008) is limiting BIM adoption as a standard working practice. These contributed to the creation of an organisation-wide BIM adoption strategy including the following initiatives:

BIM adoption strategy

– Definition of project modelling requirements at commencement:

  – BIM deliverables to an agreed standard (2D and 3D assets with attributed metadata at specified Levels of Development (LODs) and documentation generated from federated and solitary models where necessary);

  – Documentation: BIM inclusion in Project Execution Plan, internal and collaborative BIM Execution Plan (BEP), model production and delivery plan, quality assurance processes and Employer's Information Requirements (EIR);

  – Responsibilities for these deliverables: regional BIM leads, project BIM lead, discipline BIM coordinator and information managers; and

  – Coordination points throughout project development: BIM kick-off meetings, coordination reviews and end-of-stage BIM reviews to identify areas for improvement and 'next steps'.

– A global network of BIM leads tasked with forwarding consistent utilisation and capabilities in BIM and related computational engineering in each region;

– Development of object templates for use in BIM environments, creating a common standard for modelling and interaction with bespoke tools for replicable task automation; and

– Regular knowledge sharing sessions demonstrating the latest capabilities and providing a forum for questions, discussion and solutions.

4.2.3   Organisation wide readiness survey

Following the initial investigation, the industry sponsor has adopted several new processes and tools supporting the creation, access and dissemination of design data to

facilitate more effective engineering and project management. Findings from the initial study (Gerrish et al., 2014) have since been replicated on a wider scale, sampling 229 employees across every region using a questionnaire designed to determine respondents personal and organisation-based capabilities and confidence in BIM. The purpose of this survey was to direct further implementation of BIM tools and processes, identifying weak areas in its current capabilities and build upon findings from the preceding study through organisation wide data collection and review.

The survey was administered via the organisation intranet applying a five-point Likert scale (1932) to statements such as '*I understand the reasons the organisation is adopting BIM*' and '*We have a clear vision of how we will work in the future*'. Responses were averaged to indicate negativity and positivity in response groups. The score created for each respondent was then grouped according to location, discipline, position and experience within the organisation to show trends for these groups (a breakdown of which is shown in Fig. 4.1).
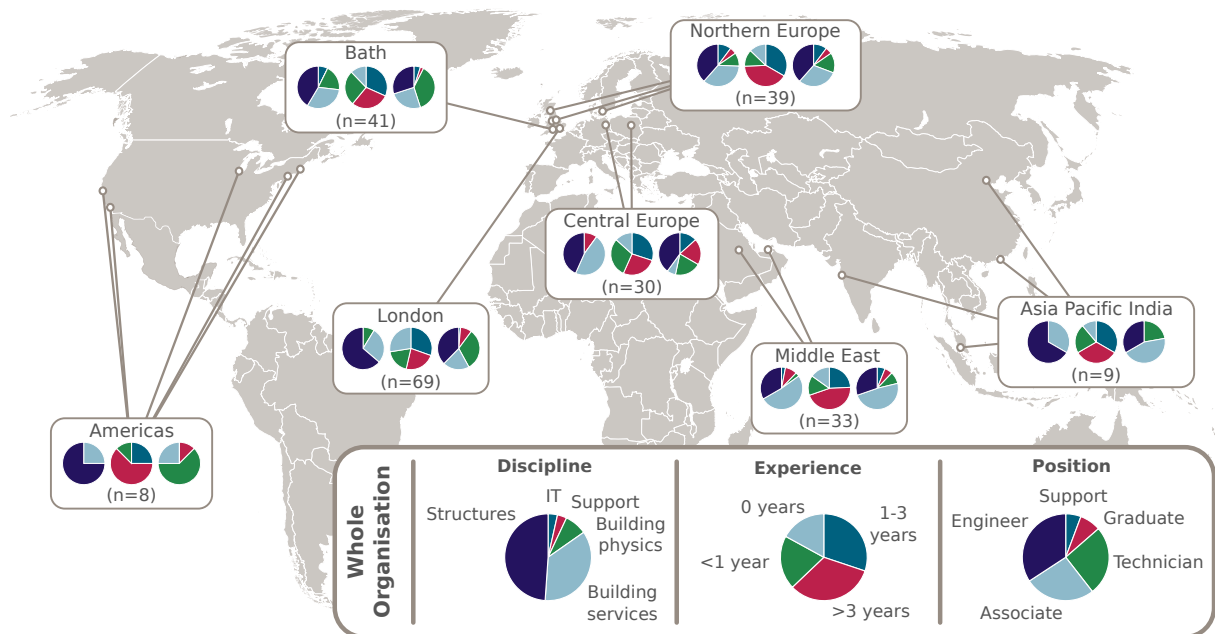
Figure 4.1: BuroHappold global BIM readiness survey response breakdown

Findings of the BuroHappold BIM capability study

This study initially highlighted the current capabilities of BuroHappold (as of mid-2013) and provided a snapshot of each surveyed discipline in terms of their BIM capabilities compared with each other. Preliminary findings from the examination of project-based capability maturity were that:

– The structures discipline was more BIM capable than building services in terms of its utilisation of BIM application and information sharing, though perceived BIM maturity inversely correlates with modelling complexity;

– IT and structures were the most developed in terms of BIM adoption, (though IT representation is likely to be in line with the most capable discipline as a supporting role necessary to provide infrastructure and capacity for BIM utilisation);

– Building services has the most to benefit from comprehensive BIM adoption, due to the vast number of sub-disciplines utilising shared information;

– Building physics showed the least BIM capability, remarking that complexity of modelling in BIM means they cannot easily automate the simplification necessary to allow for reasonable simulation of physical performance;

– BIM capability on a single project is limited by the least capable stakeholder; and

– Knowledge transfer opportunities were not effectively being made use of, exemplifying the silo-development mentality previously explored in the Architecture, Engineering and Construction (AEC) industry (Egbu, 2006; Towill, 2003).

The categories described in Section 4.2.2, were used to sort interview responses into themes of Collaboration, Information transfer, Standards and interoperability and Future capabilities to enable distinction between barriers to greater BIM integration and opportunities for improvement. Findings from these interviews are discussed in greater detail in Appendix A (Gerrish et al., 2014) and are summarised below.

Collaboration

Opportunities for more effective collaboration and the barriers inhibiting cross-disciplinary working were identified as:

– The BIM maturity of a project is based on the least capable stakeholder in that process. Work between intra and extra-organisational stakeholders (where the capability of each differs) relies on compliance to a common standard of work for which input from a less capable stakeholder could reduce overall quality; and

– The push toward Level 2 BIM by the UK Government (BIM Task Group, 2011) is benefiting cross-discipline working. However, given the nature of project-based collaboration, knowledge is shared between project stakeholders and the capacity for the skills sharing outside that project is reduced.

Collaboration between members of BuroHappold's design teams is an essential part of effective design development and coordination between disciplines to support this. Echoing the findings of Fernie et al. (2003), replication of successes attained between intra-organisational project teams must be re-contextualised with consideration of the projects specific requirements and those working on it, before they could be reproduced.

The barriers to collaboration between project teams include differing resource allocation, specialist services and location, which in extra-organisational collaboration is compounded due to reduced accessibility of team members. While BIM is removing some of these, the behavioural and methodological barriers will likely take longer (Grilo and Jardim-Goncalves, 2010). Further research on this subject is detailed in Gerrish et al. (2016c) and Gerrish et al. (2017b), demonstrating how project-specific organisational silos are being disrupted through implementation of collaborative BIM processes.

Information and knowledge transfer

Findings from this theme are given below, with emphasis given to the barriers to effective transfer of information and enablers providing methods of overcoming this:

– Transfer of information between modelling platforms is possible where exchange formats exist; however, effective use of these is limited due to the problems often

encountered through user, tool interoperability or programming errors (further investigated in Section 4.5);

– Geometric and meta-data complexity in models is an issue preventing accurate and comprehensive data exchange between modelling tools. Simplification is necessary for Energy Performance Modelling (EPM) to take place (explored further in Section 4.4), but as more detailed BIM environments are created, these require simplification and the capacity of modelling tools to export and interpret this data correctly;

– The need for accurate data transfer between modelling tools has prompted development of ad-hoc scripts to interpret, convert and export data from one modelling platform to another. While beneficial on one project and used multiple times therein, application to later projects is unlikely given its project specific relevance;

– Information sharing is more limited by competency than the technological capacity of systems and networks. Opportunities for process automation are present in every project, with tools such as Revit Server (Autodesk, 2014) implemented to increase work-flow efficiency across project teams. However, utilisation of these require user familiarity and expertise in managing the information being developed and handled; and

– Knowledge transfer between disciplines is hindered by the project specific nature of the work undertaken by the industry sponsor (Gerrish et al., 2014). This is indicative of capability as a result of the mindset of stakeholders in projects rather than the technologies and skills employed in using them. BIM implementation must therefore address both the application of technologies alongside user perceptions of its application to support more effective collaboration between previously siloed information environments

Standards and interoperability

Implementation of common design development processes (such as exchange formats, standards for information extent and content and clear stakeholder responsibilities) would provide a means through which work duplication, effort to transfer information and number of errors could be reduced (Poirier et al., 2015). Interview responses suggested the following specific changes may also be necessary:

– The need for organisation wide standards for best practice implementation was noted by most interviewees, with those changes now implemented through a defined adoption strategy (described in Section 4.2.2);

– Industry bodies responsible for specifying standards, produce frameworks for implementation but supply no integrated guide between themselves for use throughout the industry for the exchange of information between disciplines;

– Creation of standard object libraries (describing building elements modelled with common and discipline specific meta-data fields) would reduce repeated modelling time;

– Use of generic objects would increase efficiency in modelling, but reduce flexibility through standardisation; and

– Use of proprietary information formats limits interoperability, resulting in additional work manually translating information or recreating data in different formats. For example, a Revit file cannot be directly interpreted by EPM tools such as Integrated Environmental Solutions – Virtual Environment (IES-VE) (see Section 4.3), but can

be partially imported with some loss of data via an open exchange format. However, errors can be introduced through incorrect export and interpretation (Choi and Kim, 2011).

Future capabilities

Future capabilities of BuroHappold's use and application of BIM as a tool, process or supporting technology were briefly discussed with each interviewee, with the common theme focussing on the automation and streamlining of slow, yet repeatable operations. Examples include the preparation of drawings and schematics from models without the need for manual intervention, and where basic inputs could automatically compute a baseline specification from which design could then progress. Additional capabilities were suggested, with potential uses given below:

– Design of building energy performance relies on accurate, up-to-date information describing a building for input into a simulation and output of predicted performance. Interpretation of BIM in a simulation tool would require consideration of all requirements of both the authoring and interpreting tool in order to concurrently create a model suitable for both design and analysis;

– Similar to clash detection in physical geometric elements, if performance was linked to modelling effectively, there may be the opportunity for performance-based clash detection where decisions made by the designer could indicate potential for problems in building operation. Without unlimited processing power this would constrain input complexity, given the need for simulation processing in addition to detailed model management; and

– The need for the designer to understand the concept of engineering in a BIM environment as data management was noted by several interviewees. An accurate and federated as-built model containing comprehensive meta-data would be more valuable than the conventional document-based handover to the building's end-user. However, this requires the recipient to be capable of using information in this format. Perceiving engineering as applied data management, developing upon initial assumptions and adjusting values describing an as-designed built asset until that asset is built and those assumptions are comparable to monitored and recorded information would enable direct comparison between design and operation; but is far from immediately implementable due to the scope of changes necessary for such a paradigm shift.

4.2.4   Summary

Task 2 reviewed BIM implementation across several departments within the organisation to asses its status, revealing that there was a contrast between distinct disciplines in their capabilities of utilising BIM tools and processes. At the time of this study, several key reasons why take-up was slow were identified:

Interoperability

The ability to move information between platforms for different uses and particularly between discipline specific proprietary tools was limited (though has become less so since

this study), resulting in duplication of effort and greater potential for discrepancy to be created through inaccurate recreation.

Silos

Project based developments tended to stay within each project, and without publication of incremental development, the benefits realised therein would not be shared and duplicated in other projects or disciplines. Application of Knowledge Management (KM) concepts and transfer of lessons learned between projects and stakeholders would benefit adoption rates.

Realised benefits

The potential gains to be realised from BIM utilisation were primarily anticipated by those interviewed, without concrete examples given in industry literature demonstrating those benefits in some quantifiable way. As such, much emphasis is placed on perceived benefit rather than measured benefit to promote greater implementation. Examples of this include the McGraw Hill Construction (McGraw Hill Construction, 2014; McGraw Hill Construction, 2010b) surveys examining industry perceived benefits of BIM, where demonstrable time, cost and efficiency improvements are not also publicised.

Survey results

Findings from the larger survey of the global organisation found that:

– The whole organisation is positive that it has the drive required to implement BIM successfully; however the means through which this can be achieved are not entirely clear;
– The most 'BIM-confident' region is the Americas, with those in the Asia Pacific India region least confident (which according to Schmitt and Allik (2005) may be a result of cultural differences in self-esteem rather than maturity in its adoption)*;
– Building services seem to be overtaking structures in terms of capability, most likely due to the focus on development in this area since the initial interviews by the organisations BIM implementation strategy aiming to increase capability maturity throughout all disciplines concurrently;
– Those with less experience using BIM tools and processes are the least confident in BIM as a means of delivering projects; and
– In terms of years of experience, employees follow the classic Gartner Hype Cycle (Gartner, 2016) with their confidence in new technology and processes, demonstrating initial excitement, then disillusionment meeting its limitations, and eventual understanding of its effective implementation. Fig. 4.2 shows this in the distinguishing of experiences and a measure of BIM confidence.

The summary results from this survey, showing each location, discipline, position and disciplines confidence in their own capability for effective BIM implementation and

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*The Bath and London offices are listed separately from Northern Europe as a reflection of the regional management structure in place at time of survey

application are shown in Fig. 4.2. The average result for the entire organisation is included for context.
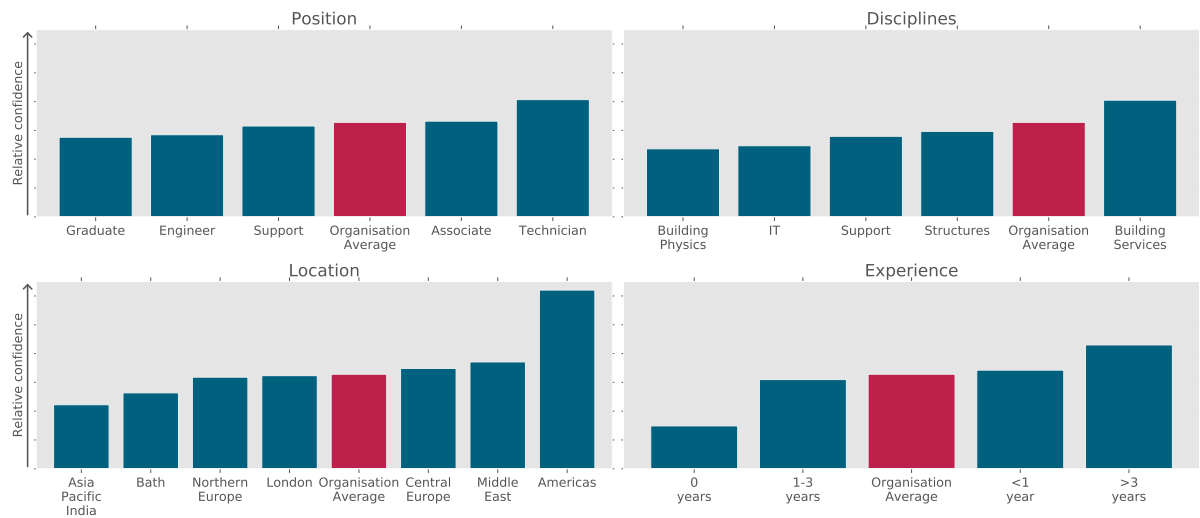
Figure 4.2: Relative confidence levels in BIM adoption and application within BuroHappold for survey subsets

The above lessons from this early stage examination of the industry sponsor demonstrated the potential for improvement in its BIM implementation strategy, through which significant changes were made over the following years, resulting in changes to the ways in which BIM was adopted and used across all major disciplines. The impact of these changes was accounted for in the research programme, ensuring work undertaken was relevant to the current and foreseen requirements and capabilities of BuroHappold. Conclusions from this long term strategy and the impacts BIM is having across the research related disciplines of building services and building physics are summarised in Chapter 5.

4.3 Task 3: Develop a framework for the generation and distribution of building performance design information around BIM

During Task 2 the lack of definitive guidance in procedures for exchange of information between the building services and building physics disciplines was noted. The opportunity to better manage information utilised by multiple disciplines and contributing to the finished project is now becoming possible using BIM. Measurement of the flow of this information in context with an amalgamated framework for its generation, storage and dissemination in line with existing design development does not yet exist, but could enable more accurate model creation through adherence to a common standard and extent of modelling for those involved.

The sub-objectives of this task were to:

– Review the current information generation, storage and dissemination methods used for building energy performance related information, and its management

requirements;

– Clarify the current process for building energy performance design, defining stake-holders and information types, and identifying areas where this may be improved;

– Examine the interoperability between BIM and EPM tools; and

– Create and apply a framework aligning existing standards categorising and measuring building performance information to BIM during building design.

This task aimed to understand how provision of information by design stakeholders could support its utilisation in later stages of a building's life-cycle, through the exploration of the information generated to support design decision making and creation of performance containing BIM. The methods used and findings from this piece of research are discussed in detail in Appendix B (Gerrish et al., 2016c), and are summarised here.

4.3.1   BIM integrated energy performance design

Several techniques were combined to provide a means of measuring performance information maturity, including qualitative methods of project review and information categorisation, with core framework development and administration

Subject review

Transfer of accurate information between design stakeholders (those involved in its generation, transfer and utilisation) was identified as a mechanism to which BIM could be applied to aid in error reduction and efficiency of the design process (Love et al., 2011; Sacks et al., 2005); though contingent to the accessibility of the necessary information relevant to each stakeholder (Laakso and Kiviniemi, 2012).

Investigation of the current status of integration between BIM and building energy performance design through literature review showed that the following elements contribute toward the slow implementation of it as a common working process, both in the specification of components in schematic design and the assessment of performance to meet adequate internal comfort criteria for regulation, the client and building purpose:

– User error and data replication inaccuracies (Aksamija et al., 2011; Leicht and Messner, 2007);

– Information ownership/responsibility ambiguity (Hjelseth, 2010);

– Difficulties in the interoperability of information across disciplines (Sanguinetti et al., 2012; Lee et al., 2011);

– Non-concurrent changes in design across non-integrated design tools (Aziz et al., 2012; Welle et al., 2011); and

– Lack of contractual requirements and guidance thereof for the handling of information for use in downstream applications (Sinha et al., 2013; Azhar et al., 2009).

Interoperability was a key theme across the reviewed literature. While design stake-holder interactions could be addressed and improved upon, full BIM implementation across all design disciplines relies upon the voluntary compliance with well-supported, but not mandated standardised exchange mechanisms and guidance documents (BSI, 2016; BuildingSMART, 2016b; BSI, 2013b; BSI, 2013a; BSI, 2013c; BSI, 2007a).

Additionally, while beneficial to project work-flows, systems managing information generated and required from the use of EPM and manual or machine assisted calculation, create derivations from existing models provided by upstream stakeholders. Such deviations contribute to non-concurrent disparate models and greater likelihood of lost intent and accuracy. Therefore, specification of exchange mechanisms between design contributors using BIM for attribution and storage of parametric performance information would provide context in which such issues are reduced. This research focussed on the categorisation (Table 4.2) and sequencing (Fig. 4.3) of parametric building and systems data, generated by each stakeholder involved in the building performance design process in a BIM environment (Gerrish et al., 2016c).

BIM and EPM framework creation

Information typologies describing major elements intrinsic to EPM and simulation and design may be broadly categorised as location, form, function, fabric and control (Gerrish et al., 2016c). The information within each may be sub-categorised by its creators and dependants in the design process in terms of its Level of Detail and Level of Development*. As the design progresses, more information becomes available as a result of design certainty and new criteria to which it must comply. This in turn, imposes constraints on the performance design, resulting in the complex interdependence of multivariate constraints contributing to a finished building design.

Each stage in the development relies on the previous providing adequate detail for progression, meaning multiple design activities utilising the same information, which could be better supported through use of data benchmarking and structuring. For example, the simulation of a building's energy performance at an early stage provides an indicative performance level from which plant requirements may be estimated. Storing simulation output in a common environment would enable Mechanical, Electrical and Plumbing (MEP) engineers and structural engineers to use that information concurrently. The processes making use of this information are shown in Fig. 4.3, with those contributing to and drawing from each indicated. The stakeholders requiring and providing information for subsequent engineering processes are clearly defined, demonstrating the key individuals in the design process and the information necessary for efficient building to be designed through collaboration. As this process describes current processes, further work was required to align this with design in a collaborative BIM environment where the information typologies and extent must be structured to effectively exchange between stakeholders and design stages.

The LOD concept defined by The American Institute of Architects and The Associated General Contractors of America (2013) gives clear indication of information extents at various stages of design progression for structural and mechanical building elements; however, this meta-data (information describing information, or in this context information describing an as-designed building) does not include all aspects relevant to building performance definition. This concept was applied to EPM inputs to outline the required information at each stage of development (Table 4.2) specifically relevant to building

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*Level of detail and level of development are often confused. Detail describes the amount of information included in a modelled object, whereas development denotes the amount of certainty in that information (McPhee, 2013b).
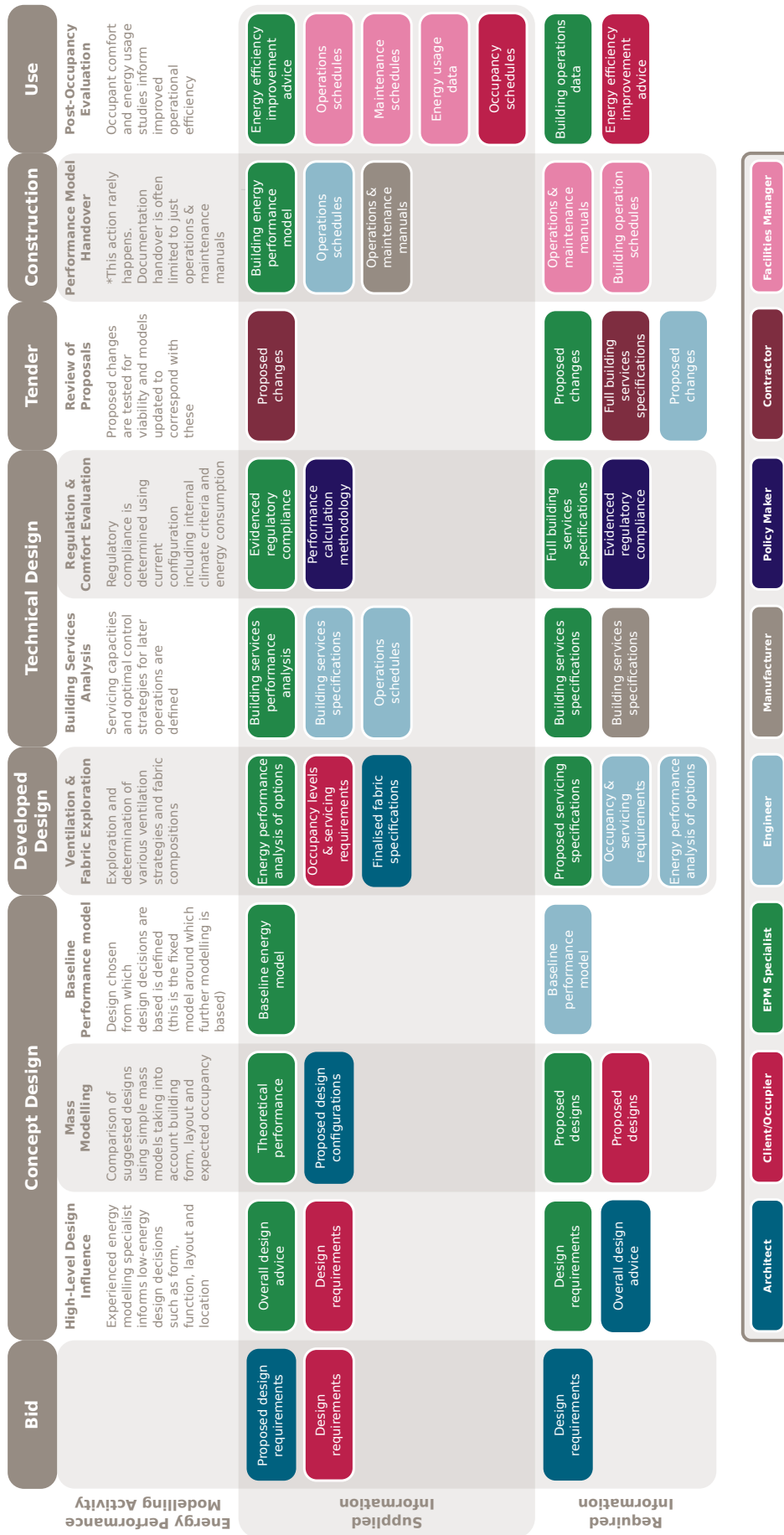
Figure 4.3: EPM stakeholder information exchange and development process

performance, for identification of key parameters to be included in design models during progressive stages of design.

Table 4.2: LOD for EPM parameters during building design

Design stage	Level of development	Key parameters
Early concept design RIBA Stage 1	LOD100 – Elements represented in model symbolically;	Location (climate, surroundings); Basic thermal zones; Generic fabric type; Occupancy, lighting and equipment thermal profiles; Generic conditions (temperature).
Late concept design RIBA Stage 2	LOD200 – Elements in model represented graphically as generic system with geometries indicated	Spatial geometry (subject to change); Fabric composition; Occupancy, lighting and equipment levels; Method of servicing (heating/cooling/ventilation).
Early detailed design RIBA Stage 3	LOD300 – Elements represent specific systems with defined location with parametric information included	Fixed spatial geometry; Detailed fabric composition (thermophysical characteristics, thermal bridging, infiltration rates); Detailed internal gains schedules; Servicing schedules.
Late detailed design RIBA Stage 4	LOD350 – Element interfaces with other systems included	Local servicing optimisation; Change in use provision; Whole building system optimisation.
Construction RIBA Stage 5	LOD400 – Fabrication and operation information stored alongside element	As-built specifications (geometry, fabric, equipment); Operation and maintenance methods.
In-use RIBA Stages 6 and 7	LOD500 – All relevant information is included ready for use by Facilities Management (FM)	External environment records; Operations and maintenance records.

4.3.2 A framework for BIM enhanced EPM

Creation of an LOD categorised framework for the creation, exchange and utilisation of information relevant to both EPM and MEP engineering, facilitated by use of BIM, resulted in the high-level definition of this information (Fig. 4.4). This procedure was developed in conjunction with partial application to varying stages of real projects to identify suitable application; for example, in the exchange of geometry and space utilisation information between Revit models and EPM tools. The full discussion of the development and application of this framework is detailed in Gerrish et al. (2016c), which may be succinctly summarised as a review of current BuroHappold projects and implementation of information categorisation and storage within a BIM environment for utilisation by other stakeholders.

Application of the framework shown in Fig. 4.4 as a guide to the information developed to three projects under development by BuroHappold, and the further discussion of issues encountered in its generation (split between methods of information storage and exchange, skills of those utilising BIM for these purposes, and processes applied during design) resulted in several issues being identified. These were indicated by engineers following the framework in conjunction with periodic reviews of the projects to which it was applied as inductive reasoning of those issues:
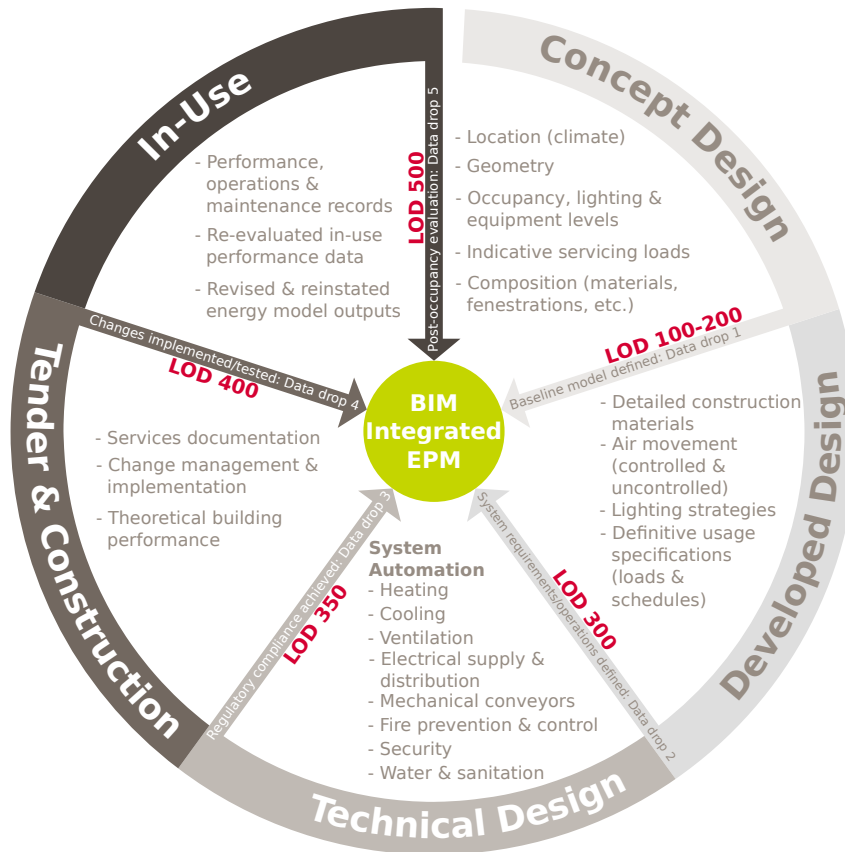
Figure 4.4: High-level EPM information for storage within a BIM environment

Methodological issues

- **Disintegrated information:** Silos of information between modelling tools for various specific purposes will remain until holistic building modelling is feasible, and contributing disciplines use a form of standardised information storage. Non-integrated platforms are necessary to support the particular needs of each discipline (Gerrish et al., 2014), but implementation of tools facilitating information exchange mechanisms (Robert McNeel & Associates, 2016; Autodesk, 2015a) are the first methodological step in moving towards a Common Data Environment (CDE);

- **Information exchange:** Open formats for information exchange (Industry Foundation Class (IFC) and Green Building Extensible Mark-up Language (gbXML)) also provide an effective means of transferring common design information across modelling platforms; however, these are limited to the information most commonly transferred using models prepared in specific ways for this transfer in mind. Typically, projects use a multitude of modelling methods resulting in inconsistent data exchange and the need to duplicate modelling downstream, potentially incorporating errors and undocumented changes. Therefore, control over changes made during modelling and records of evolving designs are necessary to document design development and enable identification of errors and clashes between composite stakeholder information; and

- **Information access:** Access to information relevant to the design activities undertaken is essential, and accuracy of that information must be guaranteed for effective

project progression. If all information was stored in a CDE, then some means of extraction for use by its dependants is necessary. Such means are enabled by the users of that CDE and their skills and capability, indicating the concurrent human challenges in interfacing change both technologically and methodologically.

Capability and skills issues

– **One-to-many models:** During application of the developed framework (Fig. 4.4), the need to remodel the same building for multiple purposes was noted in two of the three projects to which it was applied. Remodelling enabled simulation of different performance aspects, requiring different task specific configurations. This may in part be due to the skill of the initial modeller not recognising the need for a particular modelling method or purpose of modelling to support such activities at a later date;

– **CDE querying:** Data stored within a BIM environment may be made accessible to design stakeholders and building end-users, but without the skills necessary to query this information it may be made inaccessible. Modelling platforms differ in their means of storing information (for example, IES-VE stores space performance characteristics in a very different way to Revit and given the familiarity required to operate software, an unskilled individual may be unable to access this information effectively).

Procedural issues

– **Effort duplication:** Segregation of modelling for varying purposes prompts recreation of models concurrently for those purposes. This can lead to error inclusion through miscommunication of changes between design teams. Reconciling slight changes across multiple models results in inaccuracies being introduced in multiple stages of modelling and information utilisation during building design. Until model federation at a review period in design development, the error may not be recognised and performance prediction based on outdated information (Fig. 4.5);
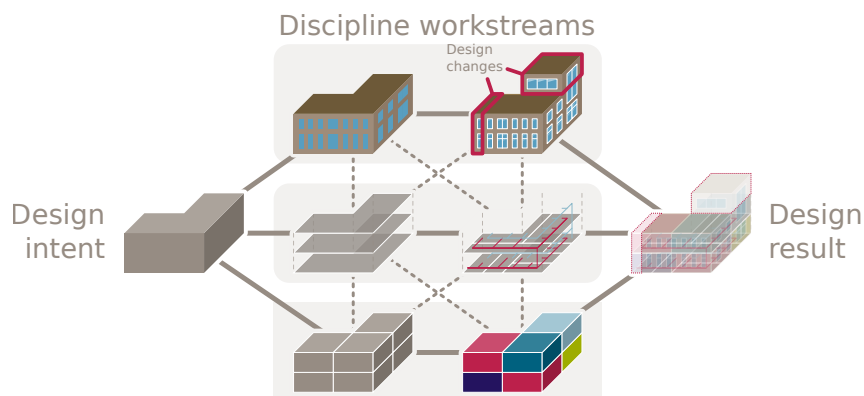
Figure 4.5: Concurrent modelling generating errors and discrepancies

– **Information validation and accuracy:** The ability to record changes made, and provide indication of errors is essential for modelling across multiple platforms. Checks between design stages must be made to ensure the information delivered

to its end-user is representative of the delivered building. Without these checks, modelling discrepancies contribute to the disparity between predicted and in-use building energy performance known as the 'performance gap' (Section 2.1.2).

The requirements for BIM application to energy performance design, information creation and communication demonstrate the range of challenges to overcome in enabling its use as an environment where performance related information can be generated and immediately utilised. Addressing procedural and skills-based issues constitute the largest challenge, as represented by previous studies indicating the slow rate of change and adoption of new working methods (Latham, 1994). However, given BIMs current and future ubiquity, the need to also target functionality of design tools is prescient to enable the adoption and training of designers in utilising those functionalities.

Objective 2: BIM use in storing and managing performance data

The second objective focussed on exploring the management of information made available during both design and operation of a building. The tasks carried out look in-depth at the information describing the performance of a building to identify opportunities for improvement in current and developing BIM methods. The findings from this objective establish the current limitations placed on the management of building performance information through BIM (Gerrish et al., 2015). The challenges facing engineering design in the twilight of 2-dimensional geometry-based CAD are explored, moving into n-Dimensional (nD) design environments* for the improvement of design-based and downstream operational efficiencies.

4.4 Task 4: Create representative models in BIM and EPM tools of an as-built building

The purpose of modelling a building's form, function and constituent systems is primarily for the evaluation of design decisions and their impact on a completed building. Measuring how each of those factors contribute toward its performance provides the designer with a better understanding of the impact their decisions have on conditional aspects of performance, where changes to these are less time consuming. This task aimed to update and consolidate building energy performance related models and information generated during design, using information gathered from a case-study projects design development directories to create an as-built modelled representation of an in-use building. This work was undertaken to provide a basis for further research into the operational performance management and investigation of a case-study building using a performance data attributed BIM. While exploratory in nature, output from this task provided a platform upon which further research could be based (see Task 7 in Section 4.7).

4.4.1 Case-study building introduction

The building used here as the case-study for modelling, and as the basis for further research is a high performance office building located in the North of England (Fig. 4.6). The industry sponsor contributed to the building's MEP, structural, ground, fire and façade engineering design in addition to providing specialist consulting on security, lighting design, acoustics, sustainability and environment. The case-study building used is representative of buildings developed at the onset of BIM adoption across the wider construction industry and within the UK. Existing methodologies for the development of engineering design and exchange processes were employed ineffectively (Gerrish et al., 2016c) given the early stages of BIM adoption, and therefore represent a complex source of information describing its as-designed and operational performance. The primary reason for use of this building

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*Inclusion of additional information in a BIM environment is often referred to as another dimension, past that of 3-dimensional geometry (3D), including; Time (4D), Cost (5D) and Life-cycle and Facilities Management (6D) related information.

was the extent to which it was to be monitored upon completion, with an extensive Building Management System (BMS) from which operational performance information could be extracted; however, as research progressed it became apparent that its choice was fortuitous and representative of the challenges present across multiple building types for implementation and utilisation of information in and around BIM environments.

Figure 4.6: Case-study building (BuroHappold Engineering and Palin, 2016)

The majority of the building comprises open-plan offices around a large atrium, conditioned using a complex Heating, Ventilation and Air-Conditioning (HVAC) system fed from two Combined Heat and Power (CHP) engines with gas boiler backups, propane and absorption chillers in conjunction with passive cooling towers and ground tempered Variable Air Volume (VAV) ventilation. Space heating and cooling is achieved via perimeter trench heating and passive chilled beams across all floors above ground level, with Fan Coil Units (FCUs) supplementing this at ground floor and in server rooms. These systems are controlled via a BMS with 28 distinct modes of operation depending on external conditions and demand for heating and cooling.

Available information

At research commencement, the building was in the process of final fit-out and commissioning, prior to handover and occupation in March 2013. Building geometry was available in Revit format for architectural and structural detailing; however mechanical services and building energy performance data were only available as 2D CAD and the proprietary IES-VE format, respectively. Engineering data and level of detail for each discipline (constituting a description of holistic building performance) available at research commencement is detailed in Table 4.3. This was collected through exploration of project filing for the case-study building, containing all models, supporting documentation and detailing surrounding the building's composition, as-designed performance and method of operation

BuroHappold's role within the case study buildings design process was as consultant engineers providing services during RIBA (2013) Stages 1-4 (with input into Stage 7 for

Table 4.3: Building models available at research commencement

Discipline	Modelling environ-ment[a]	Modelled extent
Architectural design	Autodesk Revit Architecture	Geometry (based on preliminary Sketchup models); Orientation; Fabric specification; Junction detailing; Space scheduling; and Materials scheduling (not including performance specification).
Structural engineering	Autodesk Revit Structures	Geometry (based on Architectural specification); and Element performance specifications (from Autodesk Robot and Tekla Structures).
MEP engineering	Autodesk AutoCAD	Geometry (for detailed junctions only); Electrical systems layout; Ventilation systems layout; CHW layout (including HTCHW and LTHW); DHWS systems layout; and All system performance specifications derived from discipline specific tools and calculations to Stage D detail.
EPM and sustainability engineering	IES-VE	Location; Geometry (simplified for EPM constraints); Fabric performance specifications (including glazing); Heating system characteristics; Cooling System characteristics; Ventilation system characteristics; and Space-type based thermal profiles.

[a]Modelling environment in this context is the principal data storage mechanism in which information describing a building's composition and systems is recorded. Modelling environment may also refer to platforms in which this data is generated, such as the IES-VE package and specific MEP design tools; however, these mainly serve to generate such information and provide reasoning for its implementation.

commissioning and sign-off). Creation of system accurate as-built models during these stages were not a priority and for which creation would not be feasible given the likelihood for change in construction and handover. Research into the use of BIM for managing building energy performance required the building to be supported by information stored in a BIM environment. However, the building was completed at the commencement of the adoption strategy discussed in Task 2 (Section 4.2.2), and models other than partial architectural and superseded structural models were unavailable. The client did not specify a BIM delivered project and as such the majority of the information describing the case-study building was primarily spreadsheet and drawing-based. As information was gathered from handover documentation and members of the design team and commissioning engineers, this was used by the RE to create new models in IES-VE and Autodesk Revit to standard suitable for use in later research.

4.4.2 Approach

Document review

Document review was the primary method of collecting information describing the case-study building, utilising models developed by the design team and supporting documentation to provide a comprehensive dataset detailing the building's composition and intended performance. Bowen (2009) explains the justification for documentation review as an inexpensive and unobtrusive method of gaining background information that may provide a 'behind the scenes' view of information available through more prominent sources (end of work stage reports and most recent models). However, a thorough review of all information generated during design would be too time consuming given its subjection to bias from selective information survival (where relevant information is not found due to its reporting bias surviving more favourable information (Shermer, 2014)), and potential for incomplete or inaccurate (Thabet et al., 2016) and often disorganised (Lucas and Bulbul, 2013; Hjelt and Björk, 2006; European Construction Research Network, 2005) records.
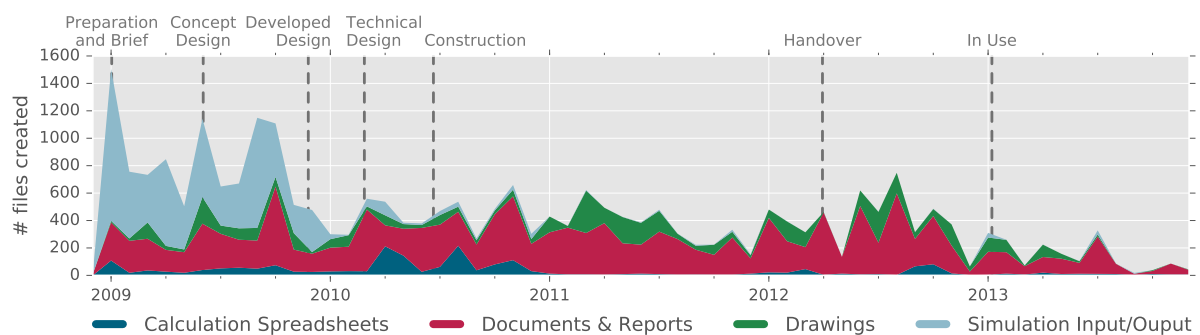
Figure 4.7: Design documentation type production frequency

A brief meta-analysis of the project's documentation structure* was undertaken showing the extent of information generated throughout design (Fig. 4.7). The majority of this

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*File-types categorised based on their associated software. For example; .csv and .xls files were designated as calculation spreadsheets and .pdf, .doc and .ppt as documents & reports. Drawings and simulation input/output were more varied, but included the common and proprietary formats utilised during case-study building design.

information would likely be out-of-date upon building handover due to changes made throughout design development, and length of time between creation and utilisation of such information. Large numbers of simulation files created at early stages are likely disproportionate due to the number of documents created to support analysis between Preparation and Developed Design.

Reports signifying handover of information for the next stage of design provided the primary source of information describing the building, and expected levels of performance; however, following handover to the specialist contractors at the Technical Design stage, changes became less documented. Handover documentation and drawings compiled into Operations and Maintenance (O&M) manuals provided the most concise and structured source of information from which to draw accurate designed performance and configuration data. However, just as Gallaher et al. (2004, pp. 3.3-3.6) found, this too contained errors from corruption in storage media and out-of-date documentation. Reliance on existing data would have likely produced further error later in research, providing justification for manual recreation of building performance and BIM environments.

Baseline performance model

The most recent building energy performance model (completed 2 years prior to research commencement) showed several key differences from the as-built building, which would result in significant disparity between design and in-use performance if comparison were to be made.

Differences between design and in-use performance depiction

A substantial difference was identified between EPM and operational management of buildings performance in how prediction and measurement of that performance differed. For example, the partial layout used in simulation simplified geometry to reduce simulation and modelling time; however, operational monitoring divided spaces in a completely different way for sub-metering (Fig. 4.8). These differences demonstrate one of the challenges in linking BIM and EPM, correlating their often conflicting modelling requirements across discipline domains (Coakley et al., 2014; Bazjanac, 2008).

Creating an as-built performance model

Representing the complex operation of spatial conditioning in an energy performance model was attempted, incorporating changes found in the operation of the building. Using IES-VE (Integrated Environmental Solutions, 2016), an ApacheHVAC space-wise simulation of air supply and extract in conjunction with calibration of space-based electrical loading based on available BMS monitored performance information was attempted; however, the complexity of the case-study buildings conditioning systems prevented wholly accurate modelling of these and would have required excessive time in model calibration (Coakley et al., 2014) for which there was little justification in the context of this research.

A simplified representation of the completed buildings composition was created without definition of the specific systems providing heating, cooling and ventilation, resulting in a less detailed and more general prediction of whole buildings energy performance, for the purpose of providing a baseline model. The method used for creation of the simplified representative model was provided by the U.S. Department of Energy (2002), which gives guidance for evaluation of holistic building energy performance and where diffuse activities

(a) Simplified EPM layout for simulation efficiency (61 spaces)

(b) EPM layout required for accurate simulation of spatial performance (79 spaces)

(c) Actual building control layout used by the BMS (36 spaces)
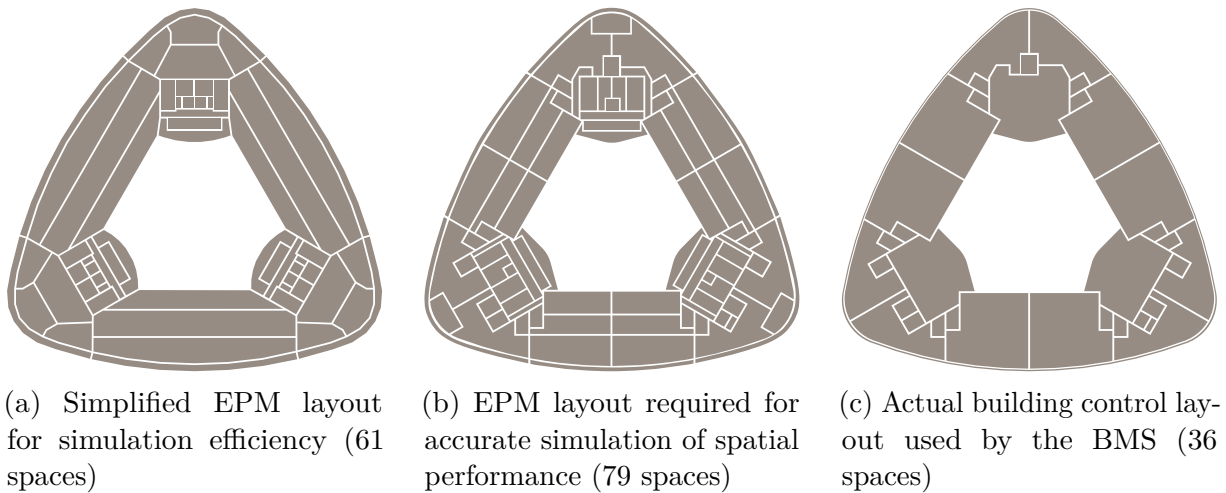
Figure 4.8: Spatial delineation differences for simulation and operation of a building's systems on a representative floor-plan

(such as changes in use and systems over time) cannot be fully represented in the model. In particular, this method was chosen given the substantive effects of each complex HVAC system of operation, making isolation of these effects complex beyond the purpose of providing a baseline energy performance model.

A BIM environment for performance data interaction

The amount of information available upon research commencement provided a rich source of data from which a BIM could be built, even when the majority of this information was stored in formats not directly compatible with transfer to a BIM environment without significant effort. The impact this has on building design development was identified by MacLeamy (2010), with Fig. 4.9 demonstrating how BIM is changing the information creation process.
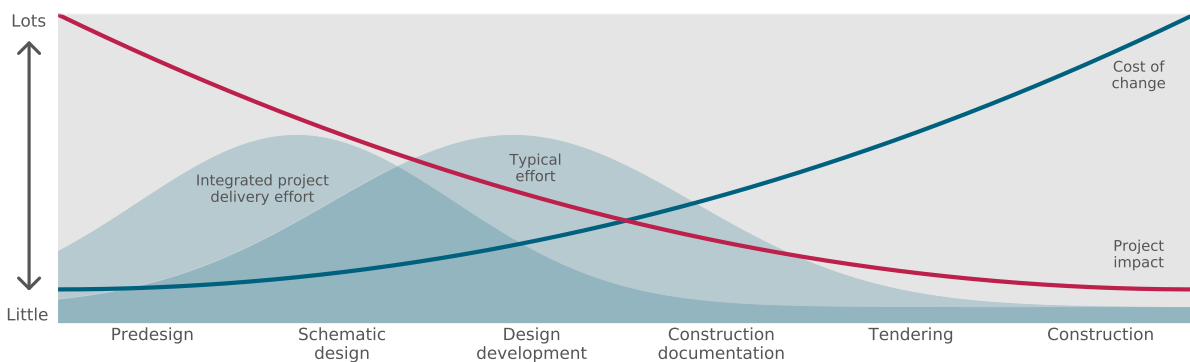
Figure 4.9: MacLeamy curve, representing the effort required to change construction design per stage of design development (MacLeamy, 2010)

During the development of a BIM in which to store building energy performance information, methods of creating and transferring information into and out of the Revit platform were attempted from existing 3D CAD models. Lee et al. (2016), Kim et al.

(2016), and Yalcinkaya and Singh (2015) all identified the potential for error inclusion in this process, with many of these errors encountered, including:

– Interpretation of space bounding elements was variable across modelling tools. EPM tools require simplified geometry, but method of simplifying this geometry are not yet available to the accuracy required for appropriate simulation use;
– Surface orientation necessary for EPM not inferred correctly;
– Intersections and slivers created as a result of poor geometry interpretation; and
– Data attribution lost between BIM authoring tools (geometric spaces ceased to be associated with their space meta-data).

In addition to user error, the remaining faults in data transfer came from incompatibility of data handling across modelling platforms, where interpretation and storage of information may differ significantly in different tools resulting in incompatible representation of the others original information (Gerrish et al., 2016c; Gerrish et al., 2015). It was therefore determined that the BIM environment should be simplified similar to the building energy performance model, to provide a platform in which data could be attributed, without excess complexity of modelling preventing any necessary changes later made to support the research. Spaces monitored by the on-site BMS were modelled (comprising all inhabited areas within the building and plant and service spaces without regular occupancy), with their design performance attributes provided by the energy performance model to provide a performance describing BIM.

4.4.3 Output

The simplified BIM used as the basis for data attribution for the research undertaken was manually rebuilt from the source drawings and models in Autodesk Revit to avoid errors in data translation, and contained basic geometry describing the building's form, with space meta-data describing purpose and predicted performance (from IES-VE) for comparison with operational data when available (Fig. 4.10). The impact of simplification of the building modelled against the as-built building had little effect on the overall outcome of this research (Section 5.3.3), given the purpose of that simplification and validity of results gleaned from data sources spaces within the model represented yet did not computationally represent through simulation. However, the need for this simplification was indicative of the extent of computing power and memory required to support the processes demonstrated in Section 4.5, necessitating more structured and efficient means of handling descriptive building performance information.

BIM and performance meta-data extraction

Data extraction from a BIM environment often requires access to the model via the same platform in which that model was created (Aranda-Mena and Wakefield, 2006); however through proliferation of open exchange formats such as IFC, information can be accessed via less costly viewing tools and open source alternatives. A Dynamo (Autodesk, 2015a) script extracting space geometry information in conjunction with related spatial performance meta-data of the case study building was created (Gerrish et al., 2017b).

(a) Space model

(b) Space meta-data
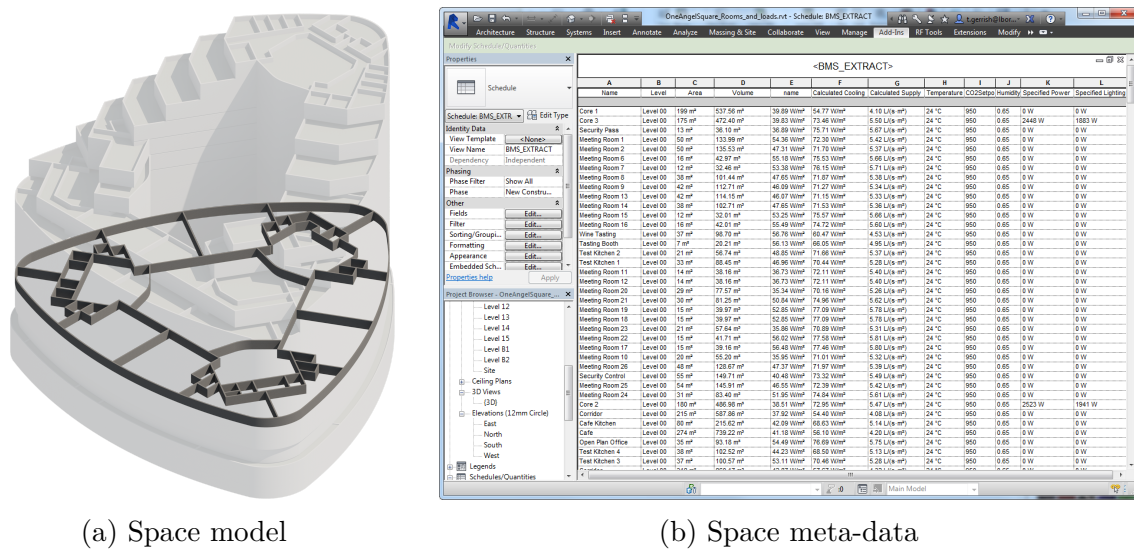
Figure 4.10: Simplified partial BIM containing only spaces and their characteristic performances

Use of these tools suggest a potential change in the role of the engineer in this process, as applied programming requires knowledge of the purpose of that programming, and where creation of scripts automating engineering processes must account for the needs of the engineer and the task. Khaja et al. (2016) and Fan et al. (2015) suggest that the skills necessary for this paradigm shift are becoming more common, yet lag behind the pace of development of tools in this area. The potential for handling of large amounts of information in this way also suggests the platforms commonly used to design, organise and access engineering related data may not be suitable (Rathore et al., 2016; Fan et al., 2015), and a need for new tools to assist in the new data paradigm.

The Dynamo script used to extract space performance meta-data from the simplified BIM shown in Fig. 4.10 is portrayed in pseudo-code in Fig. 4.11, outputting a JavaScript Object Notation (JSON) file interpretable outside any proprietary BIM authoring environment. The JSON format was chosen due to RE familiarity, its human interpretable structure and extensive support by multiple programming languages for data extraction. At this stage of research the method used to interact with this data was undefined; therefore accessibility of data was essential to support later development of BIM and building performance linking tools (further justification for this choice and description of the data extraction and interaction process given in Section 4.7).

Summary and findings

The processes undertaken during Task 4 gather information describing a case-study building, about which data was collected (see Section 4.6). Collation of this data into a set of parametrically rich models created an environment from which performance data could be extracted, linked and utilised for later investigation of BIM as a performance management tool. Several findings were made throughout the collection and utilisation of data for creation of representative models, the conclusions of which include:

– Upon creation of handover documentation (in O&M manuals and related drawings,

Load all spaces within BIM

List space performance characteristics

Write data to file

Combine lists and format as JSON

List (x,y) geometry decribing spaces

List characteristic identifiers

(a) Dynamo script


```
{
  "spaces":[
    {
      "name": "Core 2 Zone 4",
      "level": "Level 08",
      "area": 156.920254635,
      "volume": 423.684687513,
      "heating_load": 44.9440806879,
      "cooling_load": 71.7814775903,
      "temperature_setpoint": 297.55,
      "co2_setpoint": 950,
      "humidity_setpoint": 0.65,
      "air_supply": 0.0176436827689,
      "power_load": 0.000000,
      "lighting_load": 0.000000,
      "xs": [13.025212, 13.425212, ..., 11.197037, 12.625212],
      "ys": [-17.267999, -17.267999, ..., -17.267999, -17.267999]
    },
    ...,
    { ... }
  ]
}
```

(b) Revit data extract

Figure 4.11: Dynamo script with psuedocode annotation describing BIM data extraction process

guides and specifications), information describing the building is already out of date. Changes made during commissioning of the building may not be reflected in documentation, nor changes made upon occupation where occupant behaviour and use of space can vary significantly from design specifications (Wolfe et al., 2014; Clevenger and Haymaker, 2006). The result of these changes can be incorrect operation of conditioning systems to conditions no longer required, excess energy consumption through inefficient operation of plant equipment and discrepancies between the building its operational documents resulting in slower fault finding and fixing by FM;

– Requirements for simulation models do not translate well from BIM (including the quality of space bounding (Bazjanac, 2010), incorporated meta-data interpretation of simulation tools (Bazjanac, 2008) and level of detail suitable for inclusion in each (Gerrish et al., 2016c));

– Large amounts of information is being duplicated and superseded using traditional documentation methods (Section 4.4.2). Until revision control as part of BIM implementation can be implemented as a standard working process, the inclusion of superseded or incorrect documents in ongoing design development is likely to continue, furthered by the utilisation of multiple design development platforms outside federated and integrated modelling environments (Dubler et al., 2010); and

– Open exchange formats used to exchange data between modelling tools were not utilised in development of the case-study building for reasons given in Task 5. Their suitability for transferring data across different modelling platforms was partially examined in Appendix B (Gerrish et al., 2016c), but further examination of their capacity for performance data translation and storage was required (see Section 4.5).

4.5 Task 5: Investigate the capacity for building performance data attribution to BIM

The extensibility of BIM for attribution of meta-data describing modelled objects indicates the potential for inclusion of historic performance information. The models created in the previous task (Sections 4.4.2 and 4.4.2) provided a semantically rich dataset representing a case-study building and its associated performance. These were used as the basis for exploring how such performance information could be stored within and accessed via BIM authoring tools, and the capacity of existing formats for integration of operational performance data. Task 5 investigates how time-series performance data could be integrated with a BIM environment, and the applicability of BIM in its current form for use in energy performance data management.

4.5.1 BIM extensibility

The capacity for meta-data attribution in a BIM environment means potential for the integration of all aspects of design documentation including O&M manuals, records describing historical performance and changes to building fabric, systems, utilisation or operation. The single model concept discussed by Lee et al. (2012), Tanyer and Aouad (2005), and Tse et al. (2005) is yet to emerge, with industry favouring a quasi-

integrated environment in the form of federated, decentralised platforms where modelling and information storage systems share pertinent related information (Redmond et al., 2012; Sanguinetti et al., 2012; Leicht and Messner, 2007).

The concept behind attribution of meta-data for comprehensive information modelling began alongside development of object-oriented programming languages, where information could be structured for ease of collection, access and modification. The modern CDE known as BIM is analogous to this, with BIM files (both proprietary and non-proprietary) acting as a database containing objects such as geometry and pieces of HVAC equipment, and the data describing those objects interpretable by the software used to create that file.

Focussing specifically on information related to performance data (described in Section 4.3), the capacity for storage of this in the commonly used BIM authoring environment Revit and the open exchange format IFC is examined. The observations made improve the wider understanding of the capacity of BIM and their meta-data standards in relation to building performance information. This is discussed in further detail in Appendix C (Gerrish et al., 2015).

4.5.2   Data storage and access

The activities comprising Task 5 examined the potential for storage, access and application of building energy performance data within existing BIM data storage methods, in an attempt to identify whether these could be utilised as platforms about which operational performance management of a building could be achieved. The industry sponsor primarily uses Revit, which will be the platform examined in most depth here; however, alternative platforms are employed by collaborators in design projects, exchanged via convention established at project commencement.

The most common formats employed by BuroHappold for data exchange between MEP engineering and building energy performance disciplines are IFC and gbXML; however, these are seldom used in favour of recreating data manually in purpose specific software, or via ad-hoc translation tools built using C#, Dynamo (Autodesk, 2015a) or Grasshopper (Robert McNeel & Associates, 2016), and usually limited to geometry manipulation and translation. The reason for this as demonstrated by O'Donnell et al. (2013) and the research undertaken in Section 4.2 (Gerrish et al., 2014), is the inclusion of errors in automated translation and time required to fix those errors approximately equal to remodelling entirely. As methods of fixing these errors automatically are developed (Jeong and Son, 2016; Rose and Bazjanac, 2015), the opportunity for data attribution in an interoperable format grows, therefore the exchange formats mentioned previously in conjunction with the formats favoured by the industry sponsor are examined here.

Proprietary format building performance data attribution

As a proprietary software (a closed source platform wherein data stored is often intractable outside the authoring software), Revit provides the user a means of modelling and storing information in a format accessible only via itself or its Application Programming Interface (API) (Fig. 4.12). This demonstrates the capacity for static data attribution for spaces within the BIM environment; however, extraction of this information for use in external dedicated EPM tools validated using a standardised process (Judkoff and

Neymark, 2006) requires export into an accessible format such as gbXML or IFC.
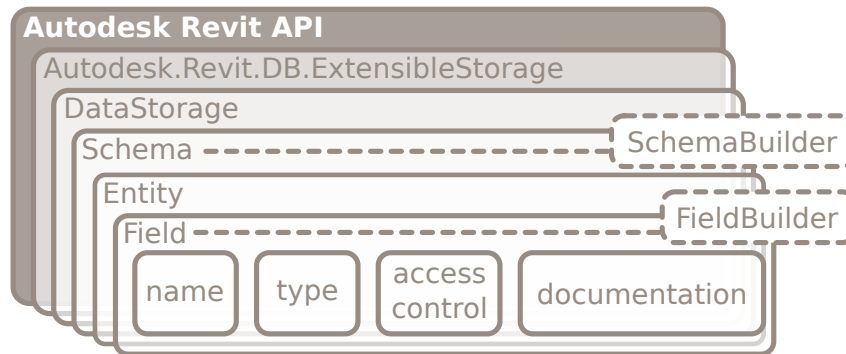
Figure 4.12: Autodesk Revit API data storage (showing an extensible high-level meta-data enhanced object)

Creation of extensible attributes in this format requires those attributes to fit conventional data types (int, double, float, bool) as well as platform specific types (GUid, ElementId, point geometry, vector, collection array, and map/dictionary array) relating to certain types of information as defined by the storage name-space. The key outcome from this is that building performance data can only be described using static information, or that which fits into one of the aforementioned types; however, building performance is non-static, continually changing as influencing factors such as users interact with embedded systems. Non-static data of this type is known as 'time-series' data, with a value corresponding to a time-stamp describing the change in that value over time. This means for use as a platform managing operational building performance information, the proprietary format utilised by Revit and its storage capabilities become unsuitable given the need for a numerical array style data type. The platform specific collection array is unsuitable for this purpose given its use as a collection of Revit objects (containing static type attributes).

Open exchange format building performance data attribution

gbXML

The majority of open exchange format files are created using BIM authoring tools with the capability to export to these formats through mapping data to a new schema fitting the specification of that open format. gbXML is the most commonly used format for extraction of geometry from such tools into dedicated EPM packages (Ham and Golparvar-Fard, 2015) due to its focus on building energy performance data. However, in tests using Revit 2013 (the version used to create the models detailed in Section 4.4), much of the information contained within the original model was not exported, including space and fabric performance characteristics held within their default attribute fields, echoing critics findings of the data interoperability issues between BIM tools (McPhee, 2013a; de Riet, 2012).

IFC

Research focussed on IFCs format due to their proliferation throughout industry as a standard exchange format between BIM authoring tools (Laakso and Kiviniemi, 2012). The IFC schema is a serialised extensible format containing a non-indexed relational

database of building characteristics, distributed as an open format. IFC extraction from a Revit model depends on the published International Alliance for Interoperability (IAI) data exchange standards and maps Revit entities to their corresponding IFC counterparts; however, this too relies on data input into appropriate fields within Revit, without which that data would be lost. Several geometry errors can be included in this process also, given the IFCs status as a lowest common denominator format aiming to support many tools for which complex geometry or data attribution may not be interpretable (Fig. 4.13).
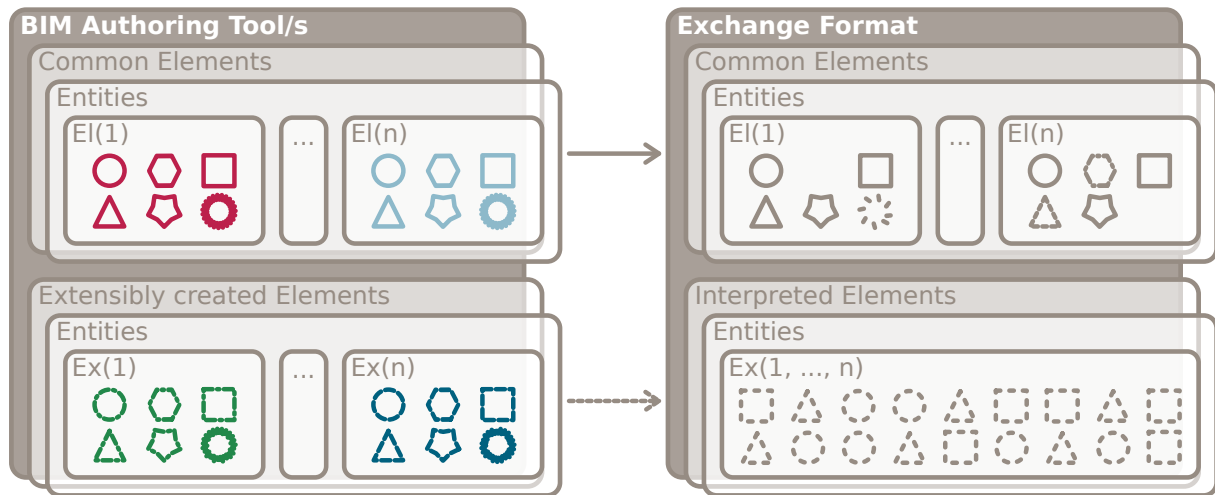
Figure 4.13: IFC as a lowest common denominator exchange format with loss of data integrity upon translation

The IfcPerformanceHistory declaration within an IFC file indicates the potential for attribution of time-series data from sources such as Building Automation Systems (BASs) and task and resources usage (related to the object in which the declaration is held). These representations could be utilised as the basis for performance logging for the management of that performance in a format already utilised by many stakeholders in the construction design and operation process (Fig. 4.14). The infrastructure is in place for this functionality, but in reality, usage of the IFC format in this manner would be prohibitive due to the amount of data that would be serialised (Gerrish et al., 2015).
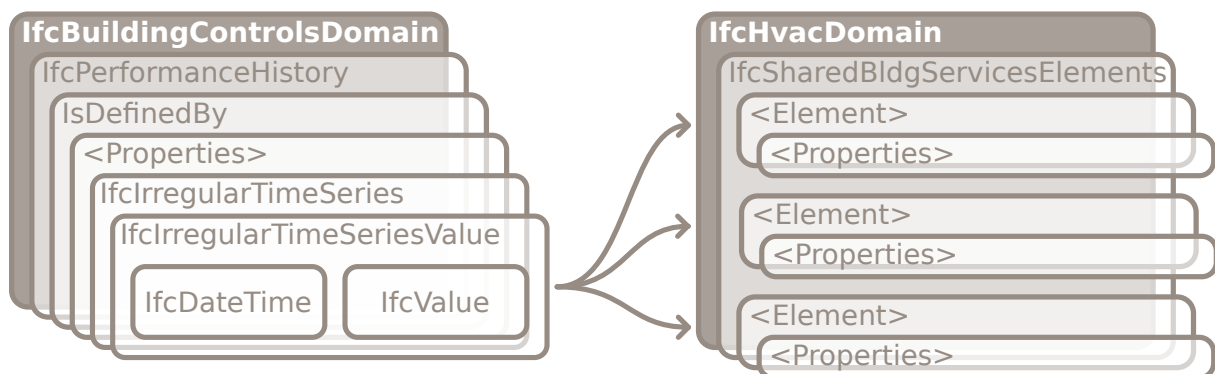
Figure 4.14: IfcPerformanceHistory and relationship with modelled elements within IFC

Testing of the IFC format for attribution and access of time-series performance data required abstraction given the lack of tools available for this purpose. Instead existing

models were used as a basis for input attributes and scaling of performance data for attribution (Gerrish et al., 2015). Exemplar IFC format models from Autodesk (2016) and East (2013) were used as the basis for this, providing a set of models of varying sizes, detail and authorship. The National Institute of Standards and Technology (NIST) IFC File Analyzer (Lipman, 2011) was used to derive high-level information about each example model file, shown in Table 4.4. The utilisation rate of property sets indicate the proportion of entities within an IFC described by a set of descriptive attributes, and therefore the entities that may be IfcPerformanceHistory attributable.

Table 4.4: Exemplar IFC descriptors for time-series performance data modelling

Model	Authoring platform	Size (Mb)	Entities	Property sets	Pset utilisation (%)
Clinic	Revit 2011	361.27	5943776	239424	4.03
Conference Centre	Revit 2015	68.38	1295929	4319	0.33
Duplex	Revit 2011	60.36	1103053	16606	1.51
Hospital	Revit 2015	66.35	1030512	5625	0.55
Office 1	Revit 2015	89.39	1579516	11603	0.73
Office 2	Revit 2011	83.44	1380805	55552	4.02

If time-series performance data is assumed to comprise an unsigned integer value between 0 and 65,535, each entry in that time-series would constitute 1 byte of data. Including a time-stamp with that value in ISO 8601 (BSI, 2004) format* would total 26 bytes. As information is recorded, attribution of performance history information to an entity within an IFC would incrementally increase file size. Fig. 4.15 shows this relationship, using an assumed file size of 120Mb (the average for those evaluated in Table 4.4), as a file to which recorded data could be written. A file of this size would contain approximately 1×10^6 unique entities for which there would be 2×10^5 property attributable objects, of which an estimated 5% could be described by time-variable attributes (resulting in just over 10,000 records).

Access to this information via existing IFC viewers would require significant computer memory, with the capacity to load Gigabytes of time-series performance data in a single file, in conjunction with related building description data which is beyond the capability of most current computers without significant changes to the IFC format.

4.5.3 Performance data integrated BIM limitations

Exploration of the attribution of time-series performance information to an existing BIM environment, indicated the potential for use of IFC for its extensibility and in-built performance history functionality. Upon testing of this method, the technical limitations of what was being attempted became clear, identifying the need for a more suitable format in which such information could be attributed. Key findings from this research identified the following:

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*A combined date and time format including time offset expressed in the form YYYY-MM-DDTHH:MM:SS+HH:MM.
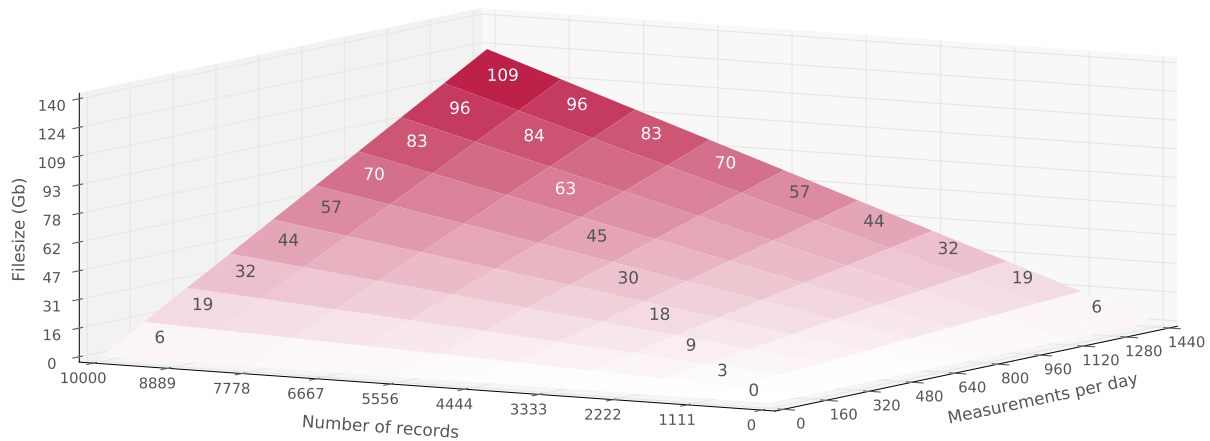
Figure 4.15: IFC file size after 1-year time-series performance data attribution (using values derived from Table 4.4)

Exchange formats

Use of exchange formats for association of large quantities of time-series performance meta-data is currently infeasible. In small quantities, IFC and gbXML may be suitable; however, conventional computers with memories between four to sixteen gigabytes cannot handle access to large amounts of data in these formats, nor do the tools exist for interpretation of such information in a computationally efficient manner (Gerrish et al., 2015).

Requirements of data storage

The requirements to which a building performance dataset must adhere, after which its use in conjunction with other tools would be possible may be defined as follows:

 – **Accessible:** The format and method of accessing this data must be such that it can be used in a variety of ways, with minimal post-processing suitable for FM and building owners to gather performance metrics. The means by which this data is held should support extraction and filtering to reduce time taken and processing required for analysis of historic data;
 – **Accurate:** Extraction of accurate data describing performance is essential for evaluation of that performance and correct feedback to building operators and optimisers. Inaccuracy may be included from many sources (investigated in Section 4.6), but must be identified and accounted for prior to conclusions reached from that data;
 – **Relevant:** The extent of information being recorded must be suitable for the purpose of its use. This pertains to resolution (the number of recordings made per time-period) and the information types being recorded, and the purpose of the information recorded (discussed in Section 4.7); and
 – **Structured:** The data must be stored in a structure from which its meaning and relationship can be inferred, or is defined in adjacent documentation. Structure depends on the method of storage (random/sequential access, location/file/content addressable, mutability), defining the limits of its immediate usability via tools required to access that information.

These findings are covered in greater depth in Section 4.6, with the full investigation

of the exchange formats and performance data attribution suitability from which these conclusions were reached examined in detail in Appendix C (Gerrish et al., 2015).

Objective 3: Developing a means of managing building performance using BIM

Objective 3 focussed on the examination of information monitored in the case-study building, and the development and testing of a means of linking existing BIM data to operational building energy performance data, monitored by the same building.

The two tasks comprising Objective 3 connect information generated during design (Section 4.4) with monitored performance via a BMS in the case-study building. Findings from this process were used to influence choices made in the development of a linking tool and provide guidance on effective data gathering and monitoring implementation in buildings. Development of tools handling this data demonstrates the suitability of currently available technologies interfacing between common BMS and BIM environments, and outlines the steps required for effective implementation in future projects using monitored building performance information.

4.6 Task 6: Investigate the performance of the existing building, identifying opportunities for improvement

Compiling the vast amount of information generated throughout design and operation is a complex undertaking, with elements of this explored in Section 4.4 for design data, indicating the amount of descriptive information generated during that stage of a building's life-cycle. The extensive performance monitoring implemented in the case-study building created a large performance dataset in which patterns of behaviour and demonstration of faults and errors could be investigated. Ahmad et al. (2016) show that implementation of such metering is becoming mandated, suggesting an abundance of such information in the future, for which methods of extraction and interpretation will be required. The limiting factors affecting this process and accuracy of information collected, such as data integrity, fault inclusion, resolution and granularity (Hoerster et al., 2015; Miller et al., 2015) are demonstrated contextually in the case-study building. Though much of this research is not intrinsic to BIM, the processes developed here are necessary for attribution of accurate performance data in later research, and indicative of the barriers to reproducibility in future applications.

4.6.1 The state of metered performance

Initially, the primary method of data collection employed was the monitoring and extraction of time-series performance data collected by the on-site BMS. However, upon investigation, the BMS showed numerous faults with errors reported across many sub-systems hindering extraction of accurate information, explained in Section 4.6.1. Following 2-years of Continuous Commissioning (CC) and regular examination of the data being collected, errors and faults were identified and reported to the FM team for adjustment.

Data collection and error handling

The BMS implemented in the case-study building used a Microsoft Structured Query Language (SQL) Server 2008 back-end storing data, referenced by software provided by Schneider based on the Andover Continuum platform. While functional, the software was built using layers of legacy systems leading to several performance bottlenecks (Gerrish et al., 2017b). Access to time-series performance data required significant training in software interaction, which in turn could not provide mass extraction given the performance limitations of the hardware and network on which the system was hosted. The most significant limitation at this point was the need for the entire systems records to be deleted periodically to reduce database size and allow the data to be queried without performance slowdown.

Querying records took time due to the lack of index on this data allowing the computer to lookup the relevant data matching user specified conditions (Churcher, 2007, pp. 183-186). For example, a time-stamp may be used as an index from which data between two times may be queried; but if all historical data pertaining to a single meter is to be queried, each entry must be searched for a matching string and returned to the user. Mass data extraction for analysis used direct interrogation from the server and the following sub-processes in order to facilitate data analysis:

– Recreation of a full database from available backups to create a historical dataset representing September 2014 – February 2016 (including indexing of data to enable responsive querying and speed up transfer times between this database and analysis tools); and

– Conversion of the restored database to a platform independent Heirarchical Data Format (HDF5) format (McKinney, 2016a) via the Python Pandas dataset handling package (details for which are included in Appendix F). This created a lightweight, multi-indexed, query-able dataset suitable for time-series analysis.

The state in which the data was stored required several error handling and reformatting routines to result in a usable dataset. The main forms of these were:

Record format

Many records required conversion between cumulative and discrete series. Memory limits of installed meters resulted in periodic resets at any recorded value reaching the maximum 16-bit unsigned binary value of 65,535 (Fig. 4.16).

Clock drift

The multiple systems controlling building operations and recording performance depended on some means of measuring time. The SQL database assigned time-stamps to each record logged based on the setting of the hardware on which it ran; however, this was not commissioned correctly resulting in no consideration of daylight saving time. Re-sampling was used to normalise records to a fixed 15-minute interval format, weighting values based on linear interpolation between the 15-minute timestamps. Where data was irretrievable, unavailable or too low in resolution to provide such detail the records were left null.

(a) Cumulative data

(b) Differential data

(c) Differential with error removal and interpolation
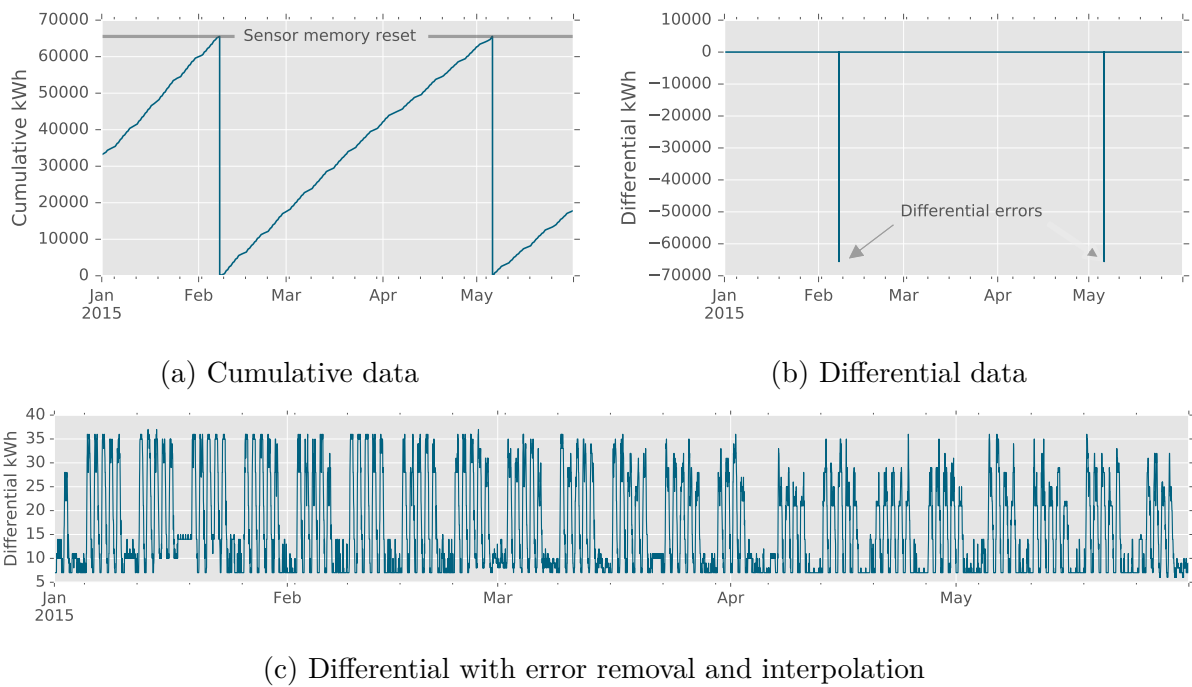
Figure 4.16: Conversion between sequential and discrete data (including meter limit reset)

Granularity/resolution suitability

Several measurements were made using the incorrect resolution and granularity due to poor commissioning For example, the energy metering measuring the amount of heat demanded by a particular heating subsystem was measured in MWh to 1 decimal place, for which the likely load level at any point in time would be a hundredth of a MWh. The cumulative result may be differentiated, but would show a low resolution view of heat demand for that subsystem (Fig. 4.17).

(a) Cumulative data

(b) Differential data with resolution differences
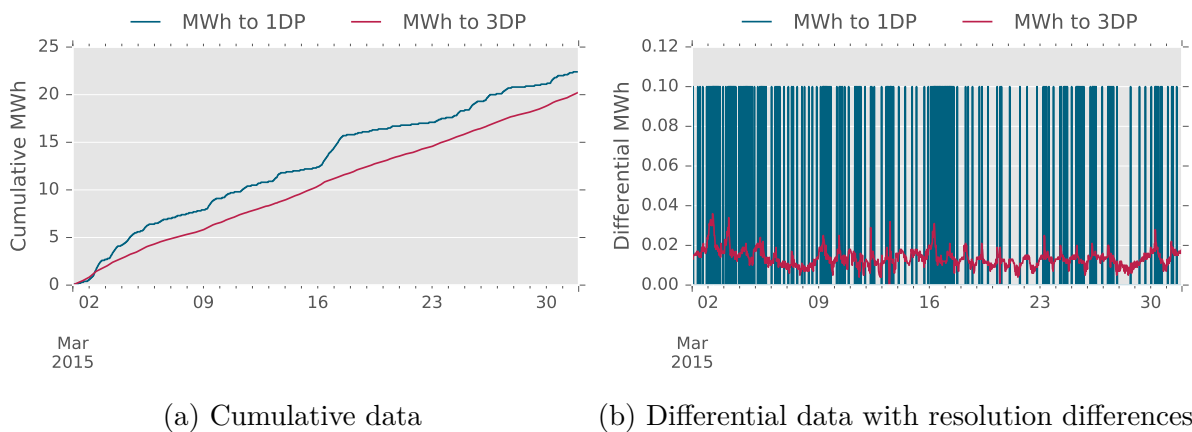
Figure 4.17: Sensor granularity and resolution impact on record accuracy

Missing data

Time periods reporting null or unchanging values while systems were operational were handled in two ways. Gaps smaller than 2-hours were interpolated linearly, while larger gaps were left null to not influence analysis.

Erroneous data

The number of records containing erroneous data as a result of faults and errors in recording were considerable. The variety of causes and effects of these meant a standard method of fault fixing required consideration of these outliers without reducing the integrity of the datasets available. The values expected from a time-series performance record are likely distributed either normally or multi-modally. For example, a winter profile differs from a summer profile due to different set-points for efficient operation and modified operating strategies to account for lower external temperatures. This would result in two normal distributions for controlled values within which normal operating conditions could be found. Outliers contribute to misinterpretation (Chen and Liu, 1993), the majority of which were removed using winsorisation (Wilcox, 2010; Dixon, 1960), effectively reducing the probability of their inclusion in a dataset (Script 4.1). This process replaces user-specified outliers outside the extreme percentiles of the dataset with those percentiles, from which a mean and standard deviation can be used to create a range within which non-erroneous data could be determined.

```python
# Python 'numpy' package used here (np) applied to data from a Pandas DataFrame
# data = list of values including outliers and nulls
# lower, upper = percentiles for exlusion/trimmed mean calculation
# n = number of standard deviations about winsorised mean

def WinsorisedDomain(data, lower, upper, n):
  x = data[~np.isnan(data)] # Remove null values
  lowlim, uplim = np.percentile(x, lower), np.percentile(x, upper) # Percentile limits
  x[x <= lowlim] = lowlim # Replace values <= lower limit
  x[x >= uplim] = uplim # Replace values >= upper limit
  wAvg = np.mean(x) # Winsorised average
  wStdev = np.std(x) # Winsorised standard deviation
  return [wAvg-n*wStdev, wAvg+n*wStdev] # Sensible limits
```

Script 4.1: Winsorisation procedure in Python

Determining an appropriate sensitivity for error removal required some trial and error; however, in tests conducted using randomised error attribution to robust data collected, an appropriate percentile range and number of winsorised standard deviations about the winsorised-mean could be found quickly (Fig. 4.18).

Data types and indexing

Conventional methods of recording and storing performance history in SQL databases for querying and summarising are effective means of storing large sets of data; however, implementation of these inefficiently (as was encountered in the on-site BMS) reduces capacity for their query, extraction and analysis.

The primary limitation to the capacity of the on-site BMS to provide historical performance information was the lack of indexing for any of the records following insufficient commissioning of the BMS database. This resulted in far longer query times than necessary, reducing the capability of the user to extract data describing building performance. Provision of indexes to support efficient access would need to balance the memory requirements of that index, the speed of update for thousands of meters simultaneously and the method of querying to access the indexed data (van der Veen et al., 2012).

The data types used to describe a performance characteristic influence the accuracy

(a) Original data

(b) Winsorised data
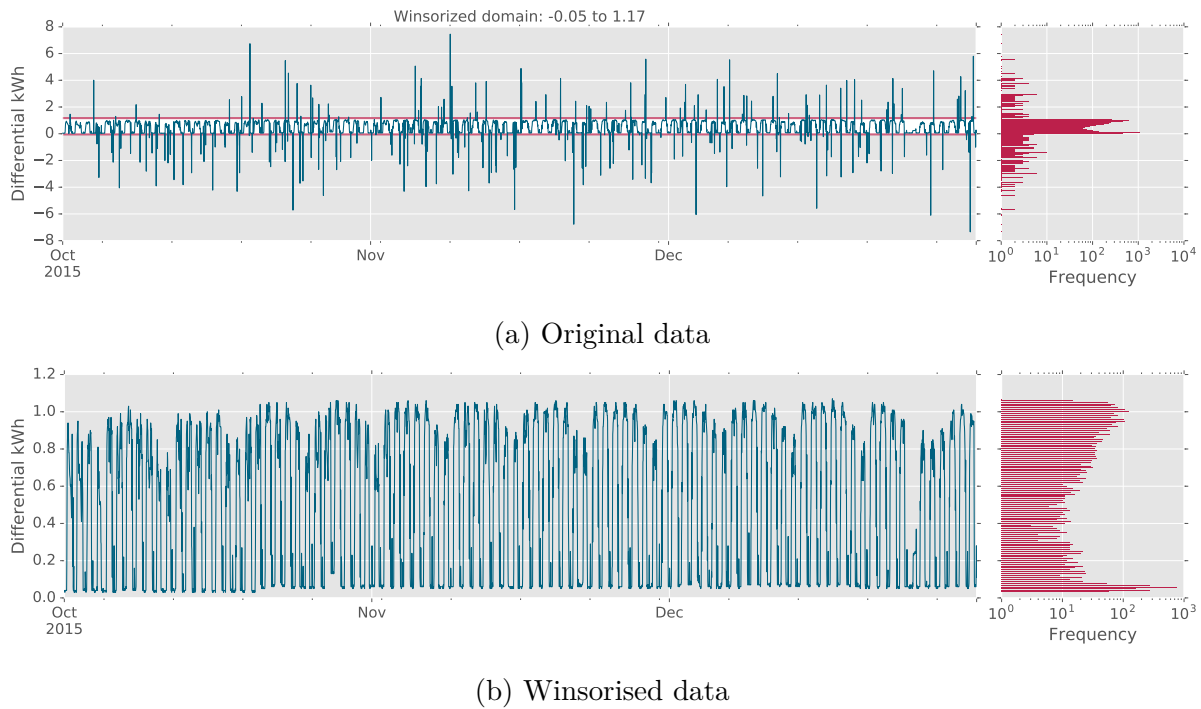
Figure 4.18: Winsorisation effects on a record containing outliers

and storage capacity required for that data. Depending on the storage method used, and data type, the storage required varies based on the precision of the data recorded (Table 4.5).

Table 4.5: Basic data types with size and value limits

Data type	Storage required	Value range
char[a]	1 byte	-128 to 127 or 0 to 255
unsigned char	1 byte	0 to 255
signed char	1 byte	-128 to 127
int	2 or 4 bytes	-32,768 to 32,767 or -2,147,483,648 to 2,147,483,647
unsigned int	2 or 4 bytes	0 to 65,535 or 0 to 4,294,967,295
short	2 bytes	-32,768 to 32,767
unsigned short	2 bytes	0 to 65,535
long	4 bytes	-2,147,483,648 to 2,147,483,647
unsigned long	4 bytes	0 to 4,294,967,295
float	4 bytes	1.2E-38 to 3.4E+38 (6 decimal places)
double	8 bytes	2.3E-308 to 1.7E+308 (15 decimal places)
long double	10 bytes	3.4E-4932 to 1.1E+4932 (19 decimal places)

A *char* also denotes letters based on the method of encoding interpretation of the environment in which that *char* value resides. For example, in UTF-8 encoding (Unicode, Inc, 2016) (where each character is 8-bits or 1 byte long), the letter A is the 65th character after formatting codes, numbers and punctuation, and is represented in binary as 65 or 01000001 constituting 1 byte.

Improving accessibility of data within a building performance database requires consideration of the number of records being collected, the format of that data (boolean, integer, float, string, etc.), update frequency, hardware capacity and extraction requirements. Recommendations for these are not within the scope of this research, but are briefly

discussed in Section 5.4 and Appendix E (Gerrish et al., 2017b).

4.6.2 Data aggregation for pattern and fault finding

During exploration of the monitored performance data, a method for analysing aggregated time-series data to identify potential performance deficiencies was developed. Space temperatures within the case-study building were used in conjunction with external temperature to provide insight into the response of those spaces to changing climate conditions and space utilisation. The relationship between the rate of change in the difference between external and internal temperatures initially exposed several potential issues identified by Menezes et al. (2012), Pegg et al. (2007), and Bordass et al. (2001); including spaces incorrectly conditioned, non-recorded changes in use and potential faults in building fabric/composition.
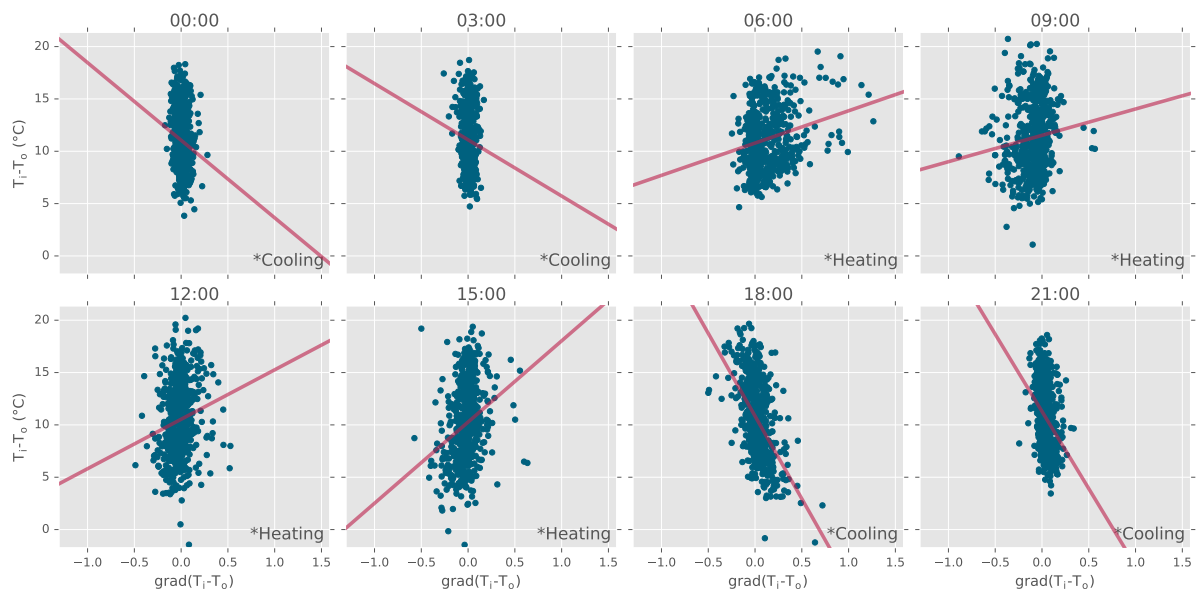
Figure 4.19: Temperature difference and rate of change for a space within the case-study building (red line indicates relationship between temperature difference and rate of change in temperature difference)

External and internal temperature for each space was compared, from which the rate of change in the resulting values were collected and grouped by time of day to give a profile for each spaces thermal response in that time period (Fig. 4.19). By comparing all spaces, outliers from the normal response pattern could be seen, from which further investigation showed deficiency in operational effectiveness of those spaces through change in use or faulty conditioning (Fig. 4.20a).

Additional details of this process and findings are given in Appendix D (Gerrish et al., 2016b). There were significant limitations to the application of this method given the case-study buildings close control strategy; however, when applied to more passively controlled buildings, clearly identifiable differences between spatial conditioning effectiveness are distinguishable.

Fig. 4.20 shows the 'thermal response' for each building evaluated in both the case-study building and a passively controlled school. While causes of different rates of internal
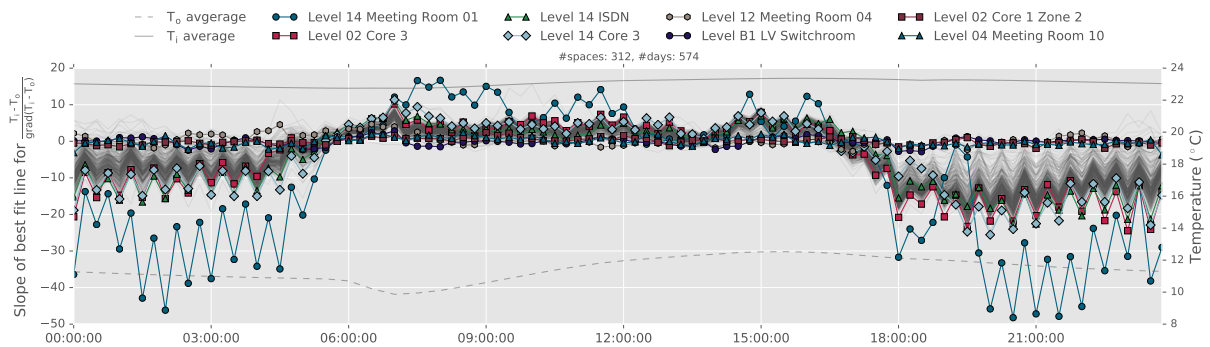
(a) Case-study building (tightly controlled, mechanically ventilated) with outliers
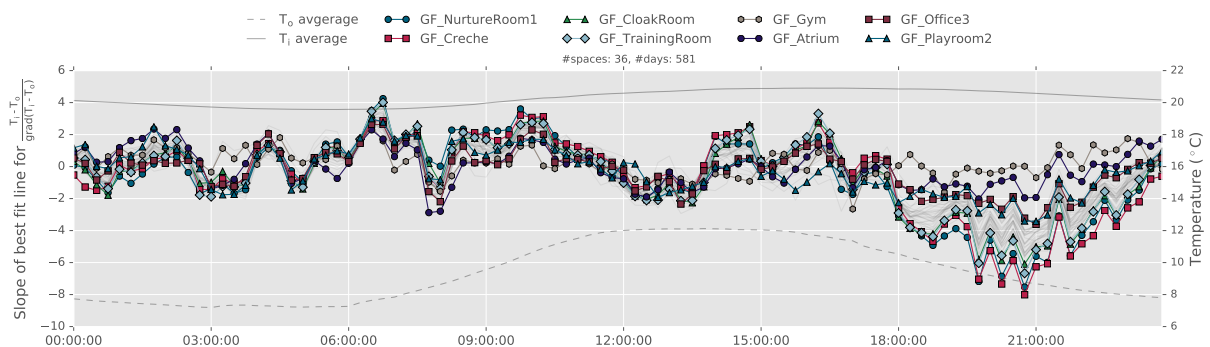
(b) School building (loosely-controlled, passively-ventilated)

Figure 4.20: Comparison between control method impact on analysis of building space thermal response

and external temperature differences are not immediately visible, the range of spatial thermal behaviours in response to changing temperature conditions clearly indicate areas where significant differences in response are experienced. Outliers in the closely controlled case-study building (Fig. 4.20a) indicate where rate of cooling past occupied hours is greater than whole building average, and where Level 14 Meeting Room 01 is potentially retaining heat more effectively than any other space (or contains an undocumented heat source). Fig. 4.20b shows greater variability in response in a passively controlled building, where the large Gym and Atrium spaces demonstrate the sensitivity of the process in identifying greater amounts of heat loss via fabric in these spaces.

4.6.3 Summary

Application of BIM to performance management through utilisation of design documentation, and access to live performance information would address performance representation for building users (Ahmad et al., 2016; Gerrish et al., 2016b), providing a platform about which a building's performance could be monitored, assessed and optimised against intended operation. The existing extensible model formats are not currently feasible containers for such extensive information (Gerrish et al., 2015); however, utilisation of their contents in conjunction with access to monitored data stored in a more efficient format is possible, and is demonstrated in Appendix E (Gerrish et al., 2017b).

This task examined the data collected from the case-study building, identifying aspects of information storage deficiency, and recording the process taken to access and interpret that data. The insights and conclusions from these findings are discussed in context with the investigation into data analysis for performance trend identification in Appendix D (Gerrish et al., 2016b). Extraction and error removal of data from the case-study buildings BMS into a queryable and high-performance data structure enabled the interlinking of that data to the BIM developed in Section 4.4. The development and application of this is described in depth in Section 4.7.

4.7 Task 7: Develop a method for the management of building performance data using design data

A method for linking predicted performance data created during design, and monitored data captured during the occupation of the case-study building was developed, applying the findings ascertained through the previous tasks. The aim being to develop a prototype for the interconnection of these two distinct yet related sources of performance information using existing technologies. A detailed account of this task including the challenges and outcomes is provided in Appendix E (Gerrish et al., 2017b).

A triangulation approach using a version of throwaway prototyping (Section 3.5.3) was applied to this task. This is the process of rapidly developing elements for incremental inclusion into a finished system. As no commercially applicable system was developed here (instead favouring the rapid development of a prototype), the composite elements created were used to evaluate the potential for, and challenges in implementing a system using BIM for performance analysis and management, demonstrating integration of the systems necessary for BIM performance management (Korpela et al., 2015).

4.7.1 Data sourcing and processing

The process of sourcing usable monitored performance data from the case-study building was described in Section 4.6.1, with the preprocessing necessary for its use in examining the building's performance also outlined. Use of this data would demonstrate the feasibility of linking BIM data with monitored data and the challenges encountered in such a process, though representing historic performance only. Ongoing performance monitoring would require changes in the methods used here, to query a live BMS database in-place of the historical data which this method uses. However, doing so would also be subject to the indexing and performance requirements outlined in Appendix E (Gerrish et al., 2017b).

Extraction from the BIM environment

The BIM environment to which that data would relate was created in Task 2 (Section 4.4), where simplification of the as-designed BIM environment was used to generate a basic representation of the building as the BMS understands it. Extraction of static design information held in that environment into a lightweight, platform independent attribute-variable format (JSON), provided a means of accessing such information without the need for proprietary software the building users may not have.

JSON was chosen due to the RE's familiarity with the format, its human interpretable structure and extensive support for parsing by multiple programming languages. Alternative formats are available, including IFC; however, in earlier investigations it was found that the existing data attribution capabilities of IFC for extensible meta-data attribute storage was limited and could potentially result in inaccessible or poorly structured data within the building model (Section 4.5). Storage in a related Binary JavaScript Object Notation (BSON) format was considered, utilising a MongoDB database (MongoDB, Inc, 2016) method of data storage; however, given the requirements for speed and portability in developing the throwaway prototype HDF5 was chosen instead (Appendix F). This method of structuring large datasets in hierarchical data tables indexed using timestamps provided and highly responsive method of accessing and processing descriptive time-series performance data.

Making BIM data accessible

Data provided upon building handover is usually held in traditional formats such as spreadsheets, documents and drawings. This secondary data, while useful for quick interpretation and extraction of meaning, does not easily support further processing due to the limits imposed upon it by the processing already undertaken. Pollock (2007) suggests the deficits to portrayal of information in this way include restrictions on access, reliance on interface-centric rather than data-centric views of information and undue effort placed on formatting of the usable data both by designers and processors, potentially limiting actions ensuring the accuracy and availability of the necessary information. Provision of data in a way to support novel use is underpinning the development of the Internet of Things (IoT) concept being applied to the AEC industry currently (Skidmore, 2015).

Utilising design-stage building energy performance data is contingent on its availability, accuracy and usability in a form manageable by the applied tools and methods. A key factor allowing attribution of building performance information to spaces and systems are comparable objects to which that data can be linked. Attribution of data to an

object representing one of these elements must utilise an identifier distinguishing that element from others, relatable between models and datasets. This was achieved here by using common space and system names between the BIM and BMS environments, but could be replicated with adherence to naming conventions and creation of dictionaries relating disparate yet related datasets where commonality is unavailable. Script 4.2 shows the JSON format used as the carrier for design-based BIM data for connection with times-series performance information from the BMS. The file this represents was created using the Dynamo script shown in Section 4.4.3, containing basic information, constituting an as-designed description of the Revit models spatial composition and performance characteristics.

```
{
  "spaces":[
    {
      "name": "Core 1",
      "level": "Level 00",
      "area": 199.094991,
      "volume": 537.556476,
      "heating_load": 85479.512854,
      "cooling_load": 117369.501888,
      "temperature_set-point": 24.2,
      "co2_set-point": 1000,
      "humidity_set-point": 85,
      "air_supply": 28.849089,
      "power_load": 0.000000,
      "lighting_load": 0.000000,
      "xs": [-7.293294, -7.107399, ..., -6.995794, -7.293294],
      "ys": [21.9836, 22.941124, ..., 20.854315, 21.026077]
    },
    { ... }
  ]
}
```

Script 4.2: Example JSON format space object characteristic extracted from Autodesk Revit using Dynamo

The processing required to create the datasets supporting the link between data in a BIM environment and in performance design and monitoring systems requires skills in areas which designers and operators may not possess. Automation of these processes would be necessary for implementation in a wider range of projects, for which standardisation of procedures and design documentation would be required. Existing standards detailing the naming, storage and data handling methods in and around BIM environments (such as the Data Dictionary provided by BuildingSMART (2016a) and BSI (2007b) on which it is based), would provide the best starting point from which automation could be developed.

4.7.2   Data relation

Kohlhase (2013), Thorne and Ball (2005), Chen and Chan (2000), and Hendry and Green (1994) identify the limitations of data portrayal as it implemented in a BMS currently, with visualisation of the data being collected an integral part to the tools developed here. Those limitations include sped of access, interpretation and action through ineffective information structuring, relying on user familiarity with the document rather than self-documented logical data structuring such as that shown in Script 4.2. Following data sourcing, extraction and processing, a means of accessing both the BIM (as a JSON

file) and BMS (as a HDF5 file) was developed. The need for efficient handling of time-series performance data collected by the BMS and sensor network throughout the case-study building was essential, given the intractability of monitored data and requirement for ease of interpretation by building operators in identifying performance trends and opportunities for improvement. The existing means of querying data from the BMS was inefficient due to the lack of indexing applied to collected data in the SQL environment (Gerrish et al., 2017b), and would be an inhibiting factor in the portrayal of performance data linked to the BIM in other buildings. This was implemented in the case-study building without accessibility to information by FM without supervision by the providers of the BMS software, significantly increasing the time taken to identify performance deficiencies and trends.

The solution developed was based upon static representation of the as-designed building and its historical performance up to the point at which extraction of such data is made from the BMS; however, there is potential for a link between a live representation of the as-managed building as both a descriptive model and monitored performance, given efficient access to this data and the continuous update of a representative model.

Tools used
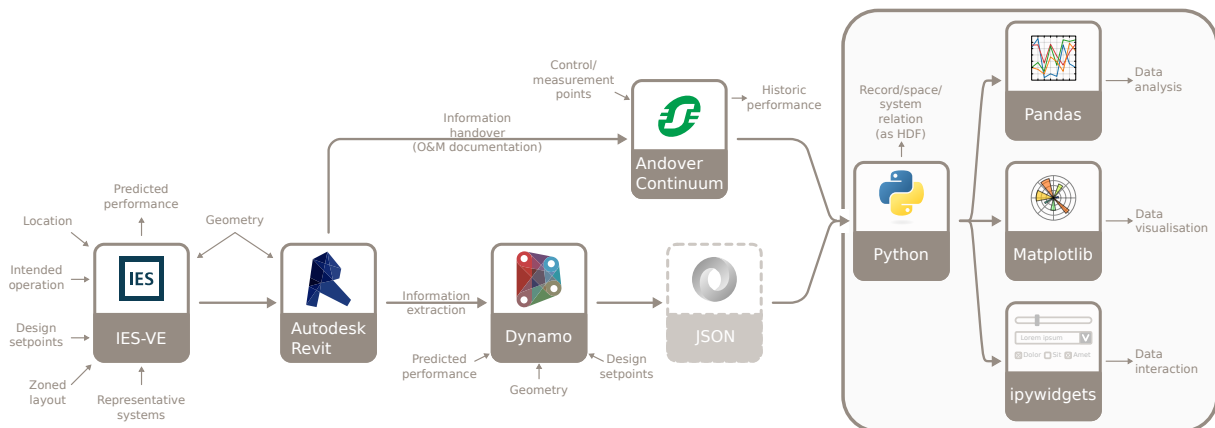
Figure 4.21: Building performance data sourcing and processing

The tools used in the development of a method for linking BIM and performance monitoring are indicated in Table 4.6. Sources of information for this process are typical of commonly used industry standard software used during building energy performance design and operation, supplemented by Python and supporting packages, included as the means through which data interoperability and interpretation was achieved between the BIM and BMS environments. Fig. 4.21 shows how the information describing the case-study buildings performance information was linked and processed in order to produce a method for the interpretation and management of building energy performance facilities via BIM. Specific types of information being passed between stages of information processing are indicated.

Table 4.6: Software used during development of the BIM-linked performance monitoring method

Software	Function
IES-VE (Integrated Environmental Solutions, 2016)	Modelling and simulation of building performance
Autodesk Revit (Autodesk, 2015c)	Modelling and attribution of descriptive performance meta-data to objects & spaces within the BIM model
Autodesk Dynamo (Autodesk, 2015a)	Attribution of simulated performance output to Autodesk Revit model
	Extraction of geometry and meta-data from Autodesk Revit into a lightweight data-interchange format (JSON)
Andover Continuum Cyberstation	Front-end interface to BMS
SQL Server 2008	Back-end BMS storage of historical performance
Python:	
Pandas (McKinney, 2010)	Extraction of data from SQL Server, cleaning of extracted data and code to interlink JSON file with query-able HDF5 performance data
Matplotlib (Hunter, 2007) ipywidgets (Pérez and Granger, 2007)	Visualisation of performance data and user interaction elements
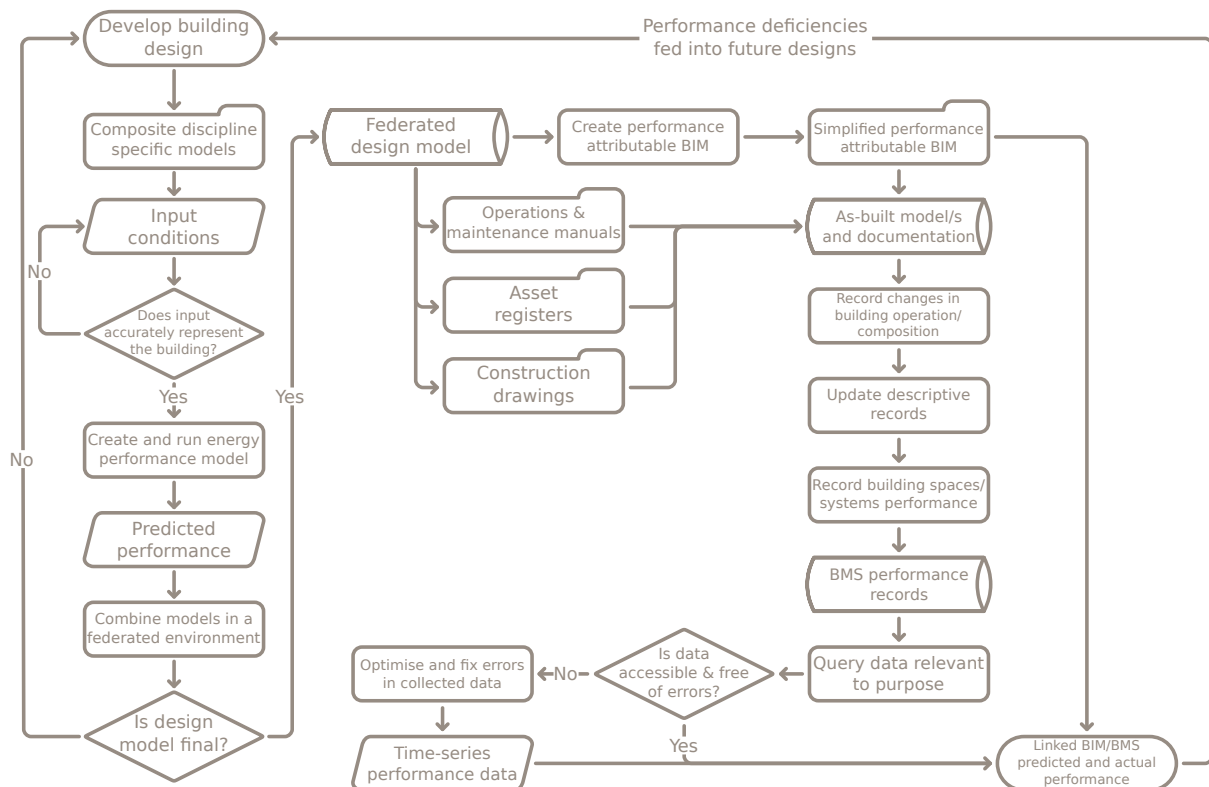
Figure 4.22: BIM/performance data information flow and linking process

Data relation process

Fig. 4.22 illustrates the process followed for gathering and linking the data contained within the distinct datasets, associating data from the BMS to objects within the BIM without specification of distinct software. The actions represent high-level processes by which the data is generated, collected and utilised from the prediction of building energy performance to its storage in a BIM environment and connection to monitored performance from a BMS. A prescriptive methodology is unsuitable for the wider industry given the non-homogeneity of design and operation methods, tools and processes, and the need for implementation considering the needs of each individual building project (Gerrish et al., 2017b).

Data portrayal

The purpose of linking design and operation data was to provide a method of performance interpretation for those responsible for occupying, operating and managing the performance of that building. The following tools supported by the BIM/BMS link developed here are shown, indicating the capabilities of such a system and its potential for BIM supporting performance management through basic interpretation and connection of data using an efficient, open and accessible method.

Space attributes

The monitored spatial performance descriptors of CO_2 levels, temperature, humidity, power and lighting energy consumption are attributed to the geometry extracted from the accessible JSON format and interpreted via Python. The quick visualisation of performance spread across spaces in a floor-plan enables the operator to identify areas of performance deficiency to focus efforts on remediation and optimisation.

A snapshot in time for Level 02 is shown in Fig. 4.23 showing spaces and their individual levels of energy consumption and conditions. Several spaces lighting and small power monitoring are not available, indicating potential errors in the sensors or BMS monitoring these.

2D-histogram of historical performance

Historic portrayal of performance in a 2D-histogram format has been demonstrated by Yarbrough et al. (2015) and Meyers et al. (1996) as providing a suitable means of efficiently displaying large amounts of time-series data. Application to the data collected show some significant trends and opportunities for improvement in the management of the case-study building.

Spatial performance characteristics shown in Fig. 4.24 show how occupant behaviour can be inferred from monitored performance, where monitoring is implemented correctly. Periods where the meeting room described in Fig. 4.24a is occupied can be clearly seen as increases in local CO_2 levels, with the space identified as unoccupied for 68% of the time during occupied hours[*]. The rate of air change can also be compared against external CO_2 levels; as the building is vacated at the end of the day and ventilation systems turn off, the amount of ambient CO_2 in the air spikes around 20:00 and returns to external ambient

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[*]During 2015 and between 08:00 and 18:30, 2343 out of a possible 3443 hours showed CO_2 levels within 10% of the external ambient CO_2 level.

(a) Temperature (°C)   (b) Relative humidity (%)   (c) CO$_2$ (ppm)

(d) Power (kWh)   (e) Lighting (kWh)
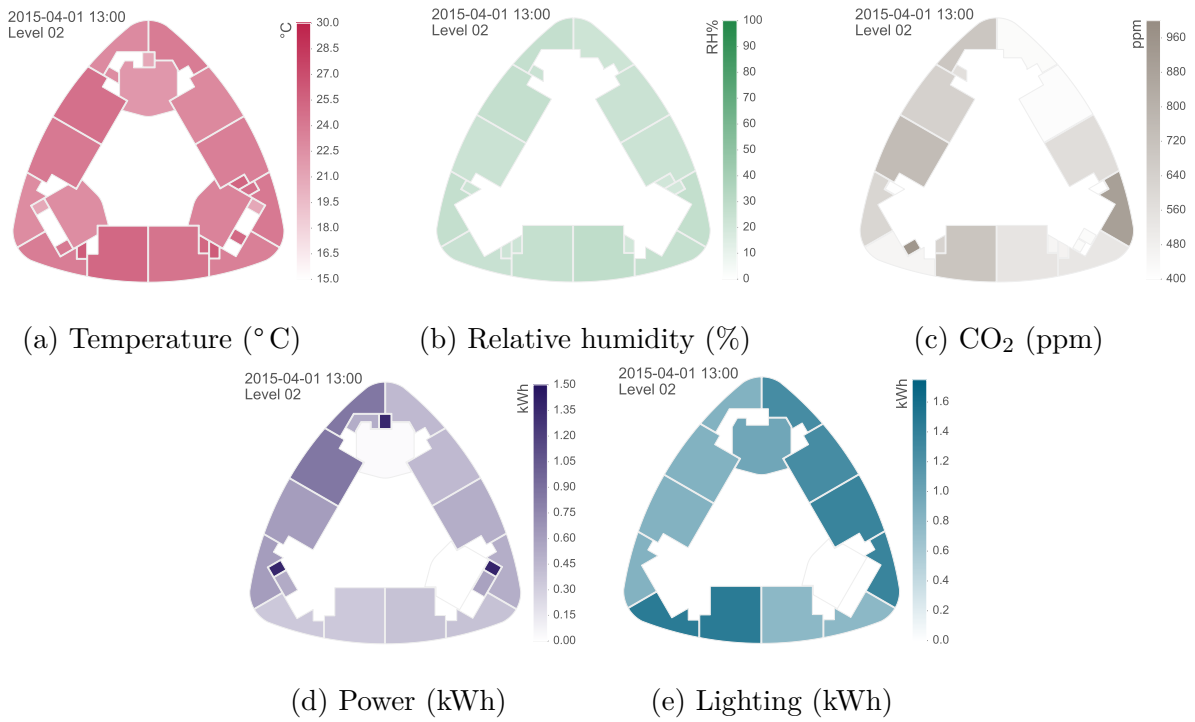
Figure 4.23: Space attributes showing 'snapshot' performance characteristics

(a) Meeting room CO$_2$ concentration

(b) Gym lighting power consumption
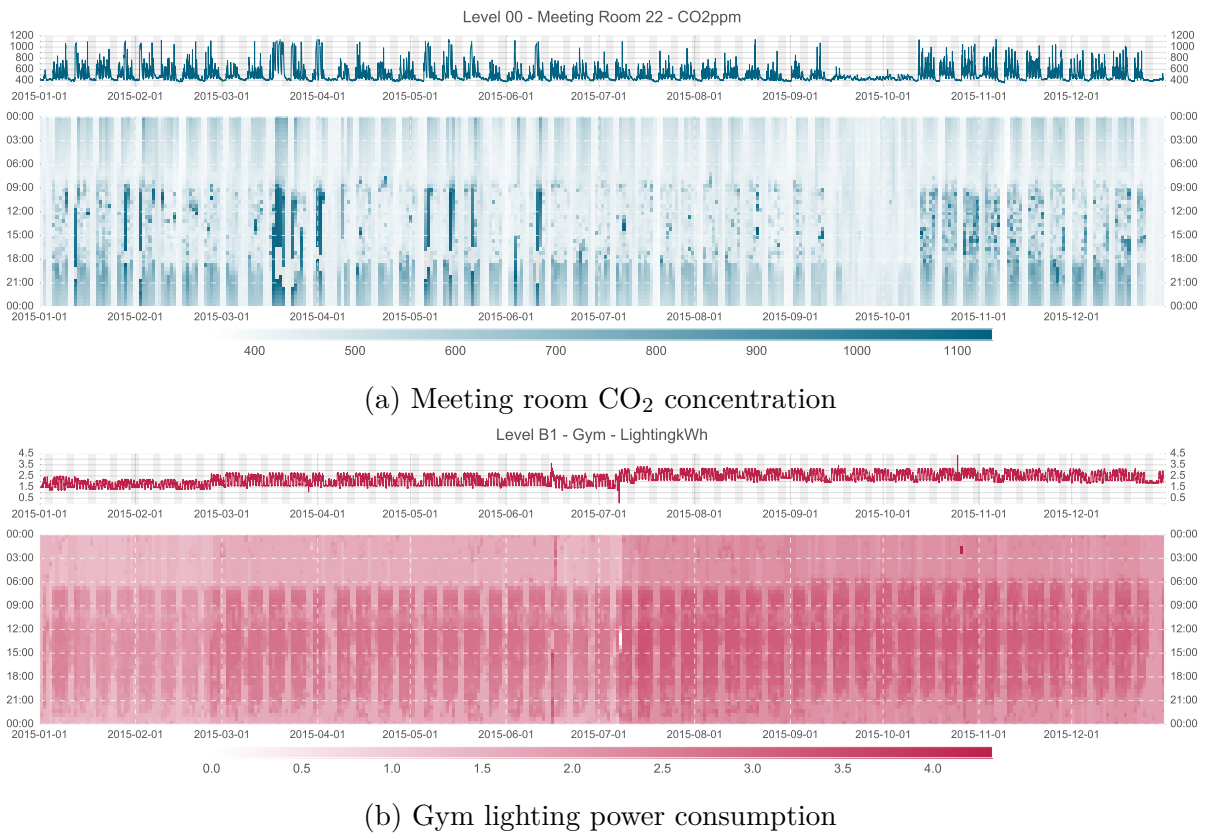
Figure 4.24: Time-series plot and heat-map spatial performance visualisation

conditions. A trend towards less efficient performance can be identified in Fig. 4.24b, with a 23% increase in energy used for lighting between the first and second halves of the year following the change in operational hours from 06:30-23:30, to 24-hour use. Lights should turn off automatically during unoccupied hours which is not happening as indicated by the 2.2kWh base load overnight following the change (a 49 % increase in unoccupied lighting loads).

Performance summary

Summarising the energy consumed by distinct spaces within the building is useful to the FM and estates management team to understand where energy has been used, and how each metered space compares to identify opportunities for improvement. Following data translation into an HDF5 file, the process used to create Fig. 4.25* took seconds rather than the hours required for extraction from the unoptimised BMS SQL database, demonstrating the room for improvement in this process. Analysis resolution can be adjusted to show more granular detail, showing the effects of holidays and the daylight dimming in-place across the level analysed (Fig. 4.25c), with user interaction modifying summary parameters to explore all aspects of the building's spatial performance.

The trends expected from such data, in-line with the patterns of use and response to external and internal climate factors are classified as multiplicative, resulting from those factors generated from differential responses to white noise inputs. As such, analysis of this data requires a combination of approaches to account for the variability between predictable (time-of-day, day-of-week, season-of-year) and unpredictable (occupant behaviour, system operation issues and unexpected) influencers. Therefore, the data obtained corresponds to periodic and sinusoidal variations, oscillating according to diurnal, weekly and seasonal differences (Shumway and Stoffer, 2006).

Aggregation for diurnal trend analysis

As the amount of data made available to FM increases, the opportunities for trend analysis of operational profiles increase correspondingly, with access to many data points from which to draw aggregate performance profiles portraying average levels of operation (Section 4.6.2). Fig. 4.26 demonstrates this, showing how the water used by the whole building varies per season and weekday, and signifying the average setback consumption outside occupied hours. While not strictly BIM application to performance management, the processes followed to enable access to information efficiently to support BIM integration, forces the monitored data to be efficiently structured, enabling analysis extemporaneous to conventional summation and averaging (Gerrish et al., 2016b).

Predicted performance disparity indication

The primary means of distinguishing performance disparity between the predicted and monitored building using the BIM and BMS data sources is achieved via the creation of a 'performance dashboard' using Python. This uses the set-points defined within the JSON BIM representation in conjunction with the data collected via the BMS to indicate levels of performance of the operational building compared with these.

Fig. 4.27 shows a snapshot of the dashboard, with interactive settings to override and adjust sensitivity settings for the indicators. Many meters are non-reporting (due to com-

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*Values at the extents of historical metering represented here may constitute incomplete weeks or months worth of data, resulting in a lower than normal summary.
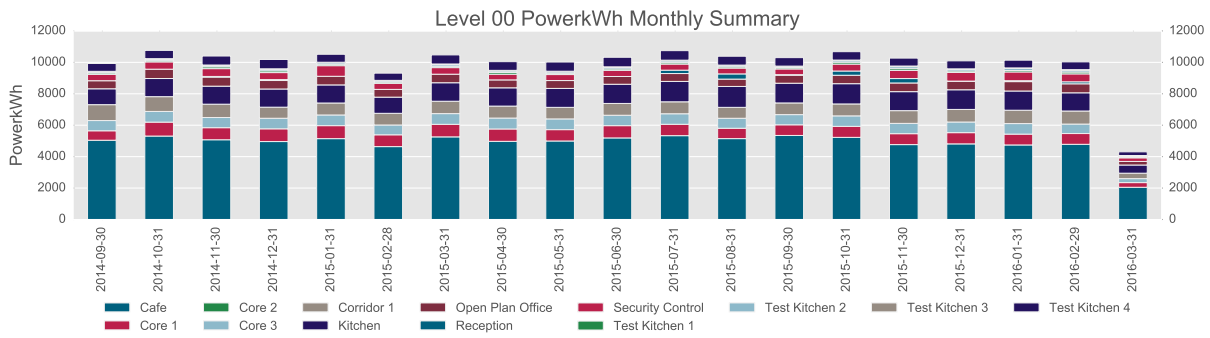
(a) Level 00 small power consumption summary
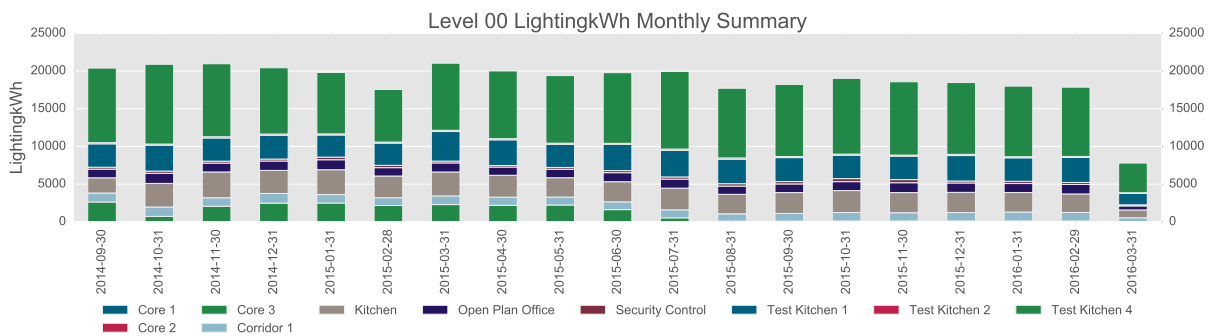
(b) Level 00 lighting power consumption summary
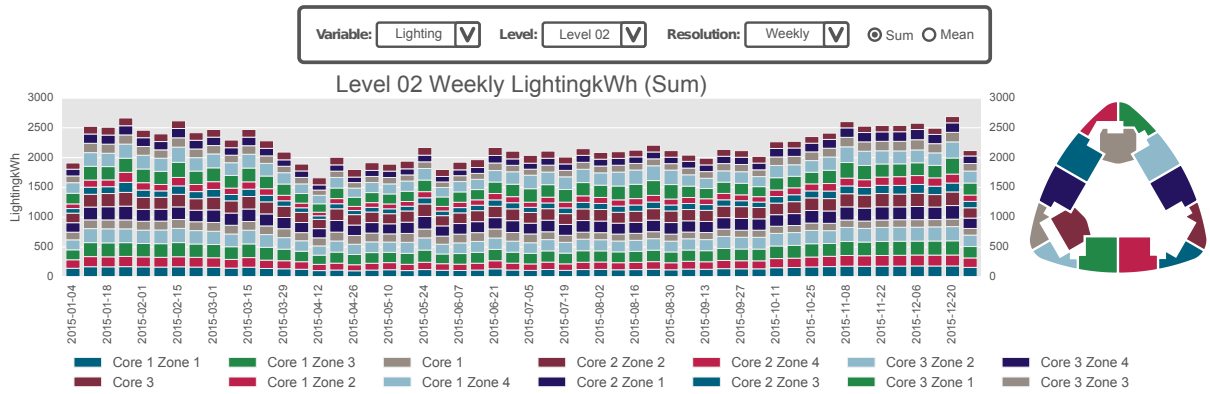
(c) User interactive performance summary

Figure 4.25: Case-study building lighting and small power summaries
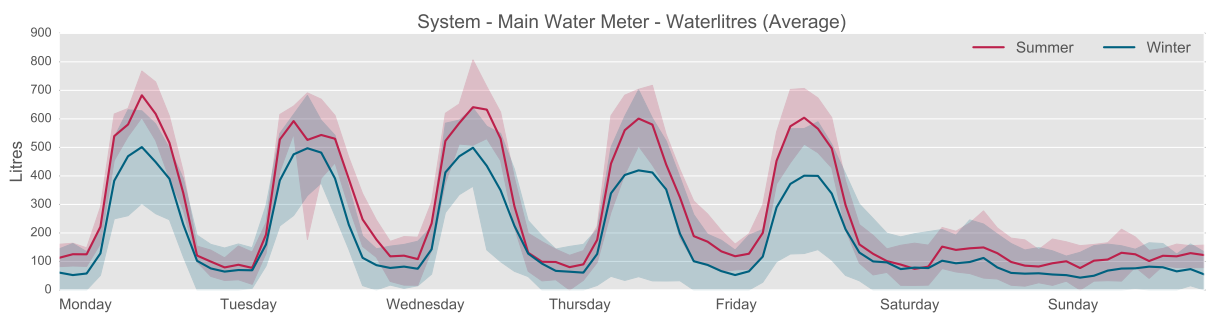
Figure 4.26: Aggregated mean diurnal profiles based on day of week and time of year

missioning issues as detailed in Section 4.4), indicating significant room for improvements in installation and commissioning of the sensors network and metering system. Spaces at above the specified maximal operating conditions are indicated for attention of the building operator.
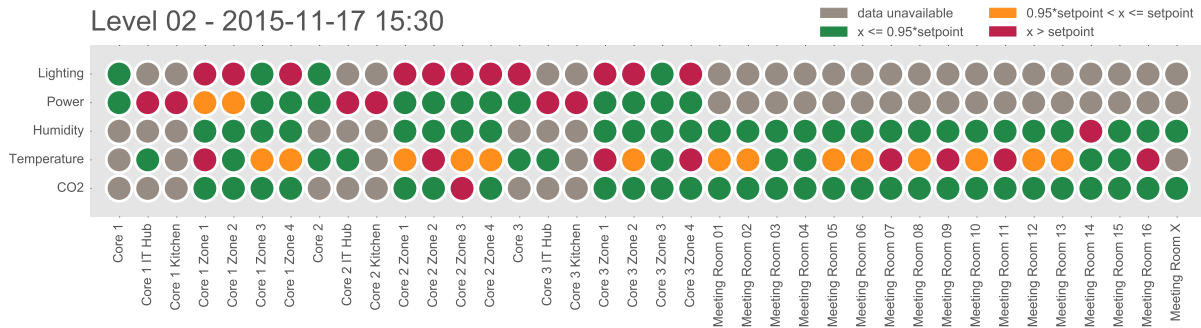
Figure 4.27: Performance dashboard indicating deviation from design specific performance for Level 02

4.7.3   Technical challenges in relating BIM and BMS data

The performance visualisations shown demonstrate the potential for BIM interoperability with monitored performance data. The methods used to create representations of historical performance identified several key technological limitations in linking these data environments, described in further detail in Appendix E (Gerrish et al., 2017b). The following technical limitations reducing the applicability of BIM for building energy performance management are as follows:

Availability of information

– While geometric description is not essential for a building user to understand how a building was intended to perform as per design specification, its inclusion in BIM is likely essential for association of meta-data and space performance attributes. The provision of a semantically rich dataset enables the owner of that dataset to extract information in context with related attributional data;

– Provision of information in O&M manuals is the point at which that information is most representative of the actual building. However, some information is likely to be out-of-date due to oversight in O&M compilation and undocumented design changes. To maintain usefulness that documentation must be maintained and updated to reflect modification and renovation;

– Significant effort is required to ensure the information contained within BIM and BMS environments are in a form suitable for linking each in the manner required. Inclusion and export of building performance information is not yet standard in use of BIM and therefore has no standard method for its incorporation and extraction;

– Creation of BIM and post-occupancy building energy performance datasets requires significant time and effort from building operators (Volk et al., 2014), reducing the likelihood that any comprehensive modelling would be undertaken to support a BIM-based energy performance management method; and

– An extensive BMS monitoring performance provides a suitable platform from which such data could be gathered, but the information recorded must be accurate and representative of the modelled objects in BIM (Section 4.4.2).

Accessibility of information

– Data accessibility limits the utilisation of that data by the extent to which that data can be accessed. As no standard method for performance data interaction within BIM environments exist, a method of doing this was demonstrated (Section 4.7.1), but the time taken to create this method is not available for all building operators;

– Proprietary formats limit the capacity of designers to manage disparate design environments concurrently, contributing to the handover of non-representative O&M documentation. However, while open standards are extensible and accessible, they are not currently implemented effectively in proprietary software to enable interoperability;

– Databases containing operational building energy performance data can be made less accessible without effective management of that data. Database management is not a common skill of a building's engineer or FM, resulting in potentially low-performance and poorly commissioned information management methods (Gerrish et al., 2017b); and

– The end-user of any system incorporating data from multiple environments must have the ability to interact with those environments (until such functionality is automated), which is unlikely given the range of possible systems and design documentation platforms information can be contained within.

Technical requirements for connection between BIM and operational performance management platforms indicate the need for procedural changes in design of building performance, its operation and management and the handling of information describing these throughout. The current software paradigm in which buildings are being designed using BIM principles and techniques (using object attributed meta-data in partially federated environments) focus on the storage of object information with the potential for its extensibility (Gerrish et al., 2016c); however, that extensibility has limits when describing variable time-series performance information (Gerrish et al., 2015). The steps required to link the design and operation data environments in their current form rely on a combination of its availability and accessibility, with extensive input from the deviser in mapping these datasets to each other (Gerrish et al., 2017b); a process subject to different challenges in each building project. A subset of these challenges are outlined in Fig. 4.28, indicating those experienced in the case-study presented here.

Objective 4: Applying and recognising the requirements for BIM enhanced performance management

The fourth and final objective summarises the research in context with designer and operator feedback in its implementation, and wider application of BIM in operational
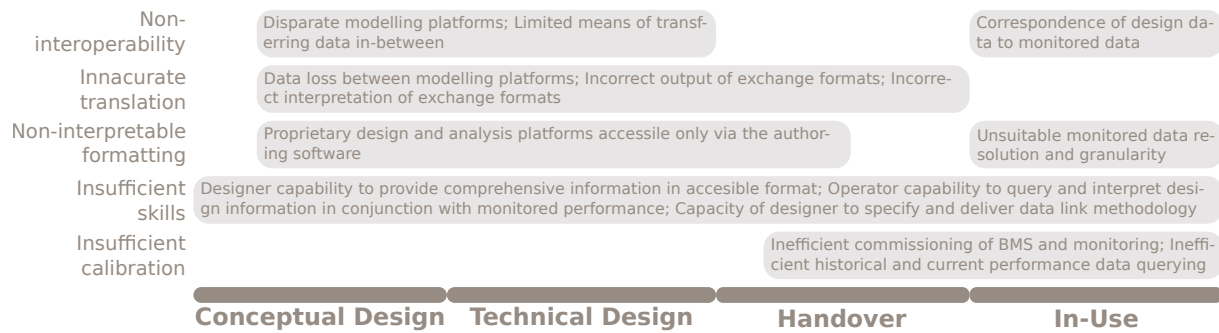
Figure 4.28: Technical factors limiting BIM utilisation for energy performance management

performance management. The findings from this objective establish the current limitations of implementing BIM-based technologies and processes for energy performance management both during design and operation; providing guidance for sourcing, producing and managing data to support the optimisation of building energy performance using BIM (Gerrish et al., 2017b). Designers and FM of the case-study building review the developed prototypes practicality, examining the requirements to consider for the implementation of a developed BIM performance management method.

4.8 Task 8: Identify potential for BIM utilisation in building performance management

In the final task, the RE demonstrated the developed method of BIM implementation for energy performance management to the case-study buildings designers and operators. Feedback from these stakeholders, in conjunction with the experiences in developing this method are compiled into a series of broad recommendations for wider utilisation of BIM in this manner. Task 8 focused on the procedural and user roles in new technology implementation to close the loop in understanding the potential for BIM-based energy performance management. Prior to development of the presented methodology, no work had been completed in directly linking predicted design performance from an industry perspective, subject to the holistic building life-cycle, and at the scale of a whole building.

4.8.1 Review method

This tasks method, while similar to that used in Task 2 (described in Section 4.2.2) explores user reaction and designer provision to the developed method using an in-depth, semi-structured interview focussing on BIM impact on the interviewee's role. The task was completed by the RE working with representatives from the case-study buildings design, handover and operations processes within BuroHappold and the clients building management team; specifically with those responsible for its operational performance, whose roles would be impacted by the implementation of the method developed. Following a demonstration of the developed method and outline of the technical requirements for supporting this, each interviewee was asked a series of questions eliciting their experiences and understanding of how BIM would impact their roles and responsibilities. Interviewees consisted of:

– The principal MEP engineer from the design team responsible for performance design and specification of conditioning plant;

– The commissioning engineer responsible for installation sign-off and seasonal commissioning of the plant equipment; and

– The building operator responsible for holistic management of the case-study buildings FM, energy consumption and optimisation.

Review of the potential for the presented method of BIM utilisation used semi-structured interviews to generate a qualitative view of potential user experience and insight into its application. The practicality of this for response collection was suggested by Elrif (2014) as limited, contingent primarily on the composition of the interviewee roles; however, the purpose of this activity was to observe and document the reactions of those whose roles would invariably be impacted by the implementation of such a tool or process, and gather their reactions. The number of interviewees is limited; though their experiences in working with the information being transferred and utilised throughout design and handover of a building (specifically related to its operational and optimisation) represent the key roles responsible for effective BIM utilisation for performance management.

The structure of the semi-structured interviews followed a time-glass model, using open questions to direct discussion toward the potential application of BIM linked to ongoing performance monitoring and management, then opening the questions again to the wider implications of implementing such a tool and the requirements to support such a capability (Runeson and Höst, 2009).

Topics of discussion

The same questions were asked of each interviewee, from which responses were transcribed and themes identified post-interview for thematic analysis in context with respondent role. Questions asked and the themes in which responses were grouped for discussion are shown in Table 4.7, within which the topics of discussion are sub-categorised into the same themes used in Task 3 (Gerrish et al., 2016c), of technology, process or person skills-related issues. Through exploration of the interviewees current experiences, and their feedback on the prototype method developed and demonstrated to them, a holistic understanding of the current and foreseeable challenges in BIM implementation for performance management purposes was achieved. Semi-structured interview topics and questions posed to interviewees are detailed in Appendix G.3.

Table 4.7: Interview questions and thematic grouping

Question	Themes
How is building performance information given to the building operator?	Methodological
How is that information being utilised?	Methodological
What drivers are influencing how performance optimisation is being applied?	Mixed
What commissioning activities are undertaken to meet expected performance?	Mixed
What challenges have arisen as a result of these?	Mixed
How do operators interface with the current BMS?	Skill-oriented
Are BIM-based technologies implemented in your operating processes?	Technical
Describe an ideal building performance management process	Methodological
What barriers must be overcome to enable that process?	Mixed

The evidence base for the findings presented here is presented in Appendices A to E (Gerrish et al., 2014; Gerrish et al., 2016c; Gerrish et al., 2015; Gerrish et al., 2016b; Gerrish et al., 2017b). This task aims to consolidate these findings in conjunction with feedback from those addressing the implementation of BIM into their working practises to generate conclusions applicable to the wider industry, and validate the research undertaken up to this point.

4.8.2 Technical issues

The technical issues relating to the effective development, transfer and utilisation of information in non-tangible forms through modelling, monitoring and aggregation were identified during the development of the BIM and building performance linking method (Section 4.7). In addition to those experienced throughout development of the prototype methodology for linking BIM to performance monitoring, additional issues were raised by the interviewees whose experiences provided a real-world perspective on challenges to consider. These included:

– Balancing the extent of detail required for building energy performance management, and the manageability of that information requires consideration of its purpose. Providing information in a manner suitable for its consumers to query, identify and extract is also necessary. Lack of modelled information may lead to a reduced number of potential uses of that information (Volk et al., 2014; Migilinskas et al., 2013); however, over-specification means larger lead times in its development, greater potential for error inclusion (due to dataset scale) and a greater need for additional skills in managing large datasets;

– Utility of information provided to the building operator is contingent on the format of that information and the end-users ability to extract from it what they require. Jylhä and Suvanto (2015) recognise this via poor documentation contributing to the paradox of there being too little information available, yet what information there is available, is made irretrievable due to lack of defined structure;

– Classification of information can be achieved currently using existing schemas (such as the guidance provided by BSI (2014), BSI (2013c), and BSI (2013b)); however, these generally only target design information. Creation of a single method for structuring all information related to a building's 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 (Gerrish et al., 2015). 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 relevant information;

– Maintenance of a model is unlikely to be completed as part of current FM activities. This would be further compounded by the need for specific skills outside the remit of FM (Tay and Ooi, 2001) in maintaining models in various BIM-related formats (Gerrish et al., 2017b). The specification of models for handover to FM for operational building management in PAS 1192-3 (BSI, 2014) indicates a more data-centric handover process, requiring receivers and end-users to manage that information as they would documentation received during handover in more conventional O&M processes;

– Handover of documentation in the form in which it was originally authored is yet to be adopted (Codinhoto et al., 2013). The reasons for this include the software required to access the information being too costly or unfamiliar to the recipients, and those recipients lacking the resources to handle the information provided (limited by skill and time constraints);

– Non-standardised extraction and interpretation of information as demonstrated in Section 4.7 is representative of the challenges facing utilisation of BIM 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 and effort required to extract this information is above that of a conventional building handover and operation process. Commercial tools to access this information directly are available; however, these incur costs in purchase and training of users, and time required for integration into an FM process for which its purpose is not fully defined (Olatunji and Sher, 2009); and

– The platforms used in the management of building performance currently are capable of handling vast amounts of information; but in order to effectively use these and interface with other technologies such as BIM, their performance must be optimised (Gerrish et al., 2016b). In the case-study building, the lack of efficient indexing of historic performance information prevented connection to the BIM due to that inefficiency. Those interviewed also expressed their concerns over the state of technologies used currently, reliant on the skills of the commissioners to implement these in effective ways. The current interface implemented prevented effective understanding of the case-study building through its limited scope for data extraction.

4.8.3 Methodological issues

While integral to the technical issues, the methodological challenges in energy performance management using BIM can also be considered independently; however, these constitute the most substantive limitations placed on BIM implementation to energy performance management. Challenges identified by the interviewees primarily concerned the procedural issues defining responsibilities in the performance management process.

– The methods by which information is recorded and exchanged currently do not best support implementation and utilisation of BIM in procedures outside building design. Collaboration between designers and operators 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 (Gerrish et al., 2017b);

– Design intent is not transferred with handover, leading to misinterpretation of information and inefficient building operation. For example, a design set-point may indicate a maximum possible value, but could be interpreted as a target value to which the building is commissioned. Documents such as the EIR have a role to play in specifying at an early stage the extent of information and format to be produced upon design completion, within which clearer specification of operational performance could be made to reduce risks of these issues occurring;

– The lack of standard methods for performance monitoring and attribution in BIM could be addressed using open exchange formats (Gerrish et al., 2015); but given

variability of operator requirements across the construction industry a new standard for such a broad spectrum is infeasible. Instead, methods of interfacing existing data infrastructures may be more suitable; and

– The technological capability to link information from various sources and implement a holistic building management platform is available; but the vision and drive of stakeholders to utilise these are not enough alone to drive its development and testing.

4.8.4 Skill-oriented issues

The skills-oriented challenges discussed during the interviews and identified in Sections 4.8.2 and 4.8.3 can be summarised in the following ways:

– New tools such as Dynamo (Autodesk, 2015a) can enable non-programmers to interface with data, but the development of skills in areas that may not be required by the end-user upon handover reduces their adoption;

– The capability of those responsible for the operation of a building to interact with and make sense of the information describing it directly influences the potential for that person to improve building performance;

– Designers who provide information must make it accessible without losing their intellectual property, just as the users of that information must not misinterpret design intent and subsequently operate their building incorrectly; and

– While not strictly a skills-related issue, contractual arrangements of FM were shown to preclude the optimisation of a building's energy performance. All interviewees indicated deficiencies in contractual arrangements for those responsible for the maintenance of a building, wherein specification of duties beyond that maintenance were overlooked as it was assumed they were an integral part of the FMs responsibilities. Integrated Porject Delivery (IPD) type models of built asset delivery may overcome this issue (Gallaher et al., 2004, p. 7.3), but are still subject to the skills held by those implementing FM processes and the methodologies leading to implementation of those processes.

4.8.5 Summary

The in-depth interviews brought up several technological (Section 4.8.2) and non-technological issues (Sections 4.8.3 and 4.8.4) impinging application of BIM as a performance management tool. Findings from Task 8 identify the technical, methodological and user-based barriers in implementing BIM as an operational performance management platform; however, its potential in supporting that management was recognised by all those interviewed during the research undertaken. In conjunction with the findings from the development of a prototype method for linking BIM and monitored performance data (Section 4.7), the consideration of data access, management and interpretation throughout the building operation process constitute a holistic overview of the challenges to be addressed in utilising BIM for this purpose.

The methods and output from Tasks 7 and 8 were compiled and published in Energy and Buildings (Gerrish et al., 2017b). In context with the wider body of work undertaken

throughout this research, conclusions and recommendations are outlined in Chapter 5.

5   Conclusions

This chapter presents the conclusions of the research project in addition to their impact on the industry sponsor and wider industry. The chapter concludes by critically evaluating the research indicating current barriers and implications to the sponsor and wider industry, after which recommendations are made for its further development.

5.1   Key research conclusions

Initial investigations contextualising Building Information Modelling (BIM) with building energy performance design and life-cycle management (Chapter 2 and Sections 4.2 and 4.3) indicated the scope of research to undertake, and the major challenges facing the Architecture, Engineering and Construction (AEC) industry currently. The research presented here constitutes a holistic review and exploration of BIM applied to performance management. It addresses some of these issues through examination of industry trends, development of a prototype method for connecting BIM with building energy performance monitoring and management, and reviews the technological and methodological requirements for its application.

5.1.1   BIM adoption and application

Adoption rates for BIM are not equal throughout disciplines contributing to the design and development of buildings and their engineering. It is important to consider the capability of each design stakeholder in the creation of information in a BIM environment. As that information is to be attributed to a model (not stored in an adjacent file as per traditional design documentation methods), the contributor's capacity to provide information in a form suitable for inclusion constrains the capability of the design team. Reasons identified for discipline disparity include:

- The variability of building typologies throughout the AEC industry;
- The amount of detail and related information potentially attributed to modelled objects;
- Complex multi-parametric relationships between objects describing and defining building energy performance; and
- The pliancy of information describing building systems throughout design and operation following documented and undocumented changes, modification to operating methodologies and multi-modal operation.

Disparities between design disciplines and the roles within those disciplines were also identified, indicating the challenges in widespread and concurrent BIM adoption globally. Where BIM utilisation was government mandated, significantly higher perceived capacity for design development using BIM was encountered (notably in the Americas region, Fig. 4.2 and Section 4.2.3). However, that confidence may also be attributed to cultural phenomena, and the composition of respondents predominantly from the structures disciplines where BIM adoption maturity was found to be greater (Gerrish et al., 2014).

5.1.2 Industry trends and developments

Summarising the literature review, the consensus towards BIM is that it offers the potential for much greater change than it is currently having throughout the AEC industry. Industry commentary around BIM is more favourable (McGraw Hill Construction, 2010b), yet lacks definitive examples of its use in favour of perceived benefits and potential for its adoption as a standard process. Theoretical benefits are difficult to translate to measurable benefits in terms of unquantifiable performance management, and cost to those utilising BIM (Giel and Issa, 2013; Gu and London, 2010). This is due to the fact that no building design project, or operating strategy is identical to another, resulting in no direct comparison for the same task utilising BIM and without.

Design and Facilities Management (FM) representatives interviewed in Section 4.8 (Gerrish et al., 2017b) as part of the research expressed similar notions that the AEC industry has the capabilities to develop some form of BIM performance management tool; however, motivation to do so is limited when each project is subject to unique constraints. This sentiment suggests the slow yet focussed development of academic research is where most change will originate. In summary, it was seen that:

– Uptake of BIM open exchange formats for design development is slow, due in part to the use of non-standard methods of classifying and modelling information across AEC projects;

– Industry perceptions of BIM were that of confidence in its ability to improve efficiency; while reluctance to adopt it as a standard method of design development remained due to the lack of exemplar projects and definitive measurable benefits it could provide; and

– Application of BIM to building energy performance management focusses on the design-side, enabling connection between BIM and performance analysis tools, and the exchange of data between them.

Future of IFC as an exchange format

As demonstrated in Section 4.5 and by Gerrish et al. (2015) the current implementation of Industry Foundation Class (IFC) as an exchange format does not support extensibility for attribution of large sets of time-series performance information. While limiting in this way, its current status as the common exchange format between BIM authoring platforms indicates its status as the most suitable candidate for open BIM during design. For wider application and adoption, it must address the following limitations identified by both Gerrish et al. (2015) and Laakso and Kiviniemi (2012), where standardisation limits applicability to novel areas; however, through standardisation with wider contextual implementation through use in International Standards Organization (ISO) standards such

as BSI (2013b) may paradoxically improve that through more widespread implementation and appreciation of its utility in wider use-cases.

5.1.3 Standards for building performance information

Information architecture was not a focus during the research, but the requirement for effective structuring of data for its access and usability was noted throughout. Existing open exchange formats such as IFC and Green Building Extensible Mark-up Language (gbXML) have the potential to be used more effectively during design as containers of design specified performance levels. However, these serialised files require significant computing memory resources when attributed extensive information such as time-series performance data and are not mature or widespread enough to be considered as platforms in which that type of data can be stored. As such, database methods of storing that information are more suited, enabling a user to efficiently query data. Current, most common protocols for the communication of systems performance within a Building Management System (BMS) include BACnet, KNX, LonTalk and Modbus among many others (further discussion is made of these in Appendix F). The number of protocols may be a result of standards not accommodating every use case, the creation of competing standards to fulfil specific needs, and their subsequent combination into another new standard (Munroe, 2011).

No widely adopted standard exists for the structuring and classification of monitored performance data; however, initiatives such as Project Haystack (2016) and Open Building Information Xchange (oBIX) (OASIS, 2016) aim to achieve this. Until such standards are widespread, the linking of live monitored building energy performance to a BIM requires the creation of an entirely bespoke system.

The following conclusions were reached through the utilisation and exploration of current methods of performance information handling and management:

– Information generated from performance simulation during design can be stored in a BIM environment; however, the amount of information to be stored there should be defined by design stakeholders based on the needs of subsequent model users;

– Structuring of measured building energy performance to a common standard is necessary to enable the development of a widely applicable method for linking BIM with an operational BMS. Current standards define the method of communicating that information, but no means of classifying it upon measurement and ensuring an accessible structure exists to support that mass of information; and

– The amount of information being recorded offers the potential for much more data processing of building energy performance to identify deficiencies. Distinguishing reasons for these deficiencies is difficult, but the generation of large datasets through extensive monitoring is creating a potential dataset to which big-data analytics could be applied for pattern recognition and holistic performance assessment.

Identifying the right variables to be measured and recorded by a BMS defines the extent of data potentially available to any tool using that information. At minimum, monitoring provides the building operator the opportunity to identify major sources of energy consumption and distinguish between end-uses for performance reporting; however, the specification of this capability during design does not include detailed recommendation for the format and types of information being recorded. As a result, the commissioning

of a BMS may not measure performance in a way suitable for its use (Section 4.6.1). Standards set for the measurement of performance and structuring of recorded data could potentially reduce these issues, including common units of measurement describing the variables being measured, and the significant figures applicable to the format in which that information is recorded. Specification of these standards could be implemented within the Employer's Information Requirements (EIR) to assist both designers in design a building for more effective operational management, and FM in interpreting what the Operations and Maintenance (O&M) handover documentation and models.

Defining a standard for data captured around building energy performance is beyond the scope of this research; however the following statements are made to assist in the development of such a standard (Gerrish et al., 2017b):

– The temptation in designing a building for efficient operation using a BMS is to over-specify metering requirements. While useful in providing a comprehensive record of performance attributes, most non-domestic buildings only require identification of fuel end-use and summary. Comprehensive monitoring does however increase potential for utilisation at a later stage. For example, in application of performance management tools as demonstrated in Task 7 (Section 4.7), and use by FM to assess and identify declining efficiency over time;

– The format of performance information recorded during building operation impacts the computing requirements of the system in which that data is stored;

– The types of information being collected should be measured to an accuracy from which detail can be extracted. For example, measuring electricity consumption in kWh to 3 decimal places would enable most relevant variables to be measured accurately and without loss of detail, whereas MWh to 1 decimal place would be too coarse a unit to distinguish changes over time. This standard for operational performance information recording should be specified in the EIR and documentation transferred upon handover to the BMS commissioner to enable accessibility and interpretation of monitored performance; and

– Commissioning of a BMS and server-based historical performance database should enable the building operator to expediently query that system. A balance should be made between the indexing of data for efficient access, and identification of frequently updated and rarely queried records for which indexing would be unsuitable.

5.1.4 Challenges to overcome in BIM application to performance management

The potential for BIM application to areas outside design and building information management is evident from the number of publications detailing novel means of utilising the information and processes therein. The capacity to utilise BIM for non-conventional purposes (such as building performance management) is available. However, the skills necessary to support this, and related time and motivation to do so is lacking in an often tightly constrained industry where focus on reduction of time and cost precludes innovation (Davies and Harty, 2013; Junghans, 2013; Gann et al., 1998). Development of tools to assist in the management of information, and therefore the performance of a building described by that information, requires coordinating effort across disciplines to

align various technologies in order to make the best use of that information and enable its interconnection with related yet currently disparate data environments. The supporting infrastructure necessary for that process is not yet developed around BIM given the time taken for technologies to be embedded in the design process, skills to be developed to best utilise those technologies, and wider exploration of its potential following recognition of benefits.

Behavioural challenges are likely the largest to overcome (Vokes et al., 2013; Peansupap and Walker, 2005). While not explored in depth in this research, one such method of addressing this is during eduction of those entering the industry in the roles impacted by implementation of BIM in this manner. Improvements in skills would still be subject to slow adoption, but as buildings move towards digital delivery in conjunction with their physical construction, those responsible for their management and operational much have the requisite capabilities to interface with that type of information delivery. Tools used as industry standard methods for the creation and management of building data are used in an amalgam of conventional design activities, in addition to their capabilities for meta-data attribution and model federation. These issues represent the far wider challenges across the AEC industry of slow technology adoption and utilisation.

The development of a prototype method for applying BIM to energy performance management experienced many challenges in using information stored in BIM environments in conjunction with external data sources. Following this development and the in-depth interviews with representatives of the building performance design, commissioning and operations processes, the following generic conclusions were reached:

– Effective utilisation of information describing building performance relies on that information being accessible, accurate and structured so that it may be queried and representative of the physical attribute it describes. Structuring of information is currently employed in models formats such as IFC, but not made accessible to those without the software used to serialise that information;

– Predicted performance information is only as accurate as the assumptions and methods used in the prediction of that performance;

– Variability between non-domestic buildings necessitate the individual handling of each use-case, but given the number of buildings and experience of operators there may potentially be some standardisation of procedure for performance improvement in conjunction with application of BIM to support this; however, commercial interest of software providers supporting development of building using BIM may detrimentally impact the capacity for utilisation of information stored in their software and proprietary formats in this manner;

– Maintenance of information in a BIM environment is essential if that information is used and modified during the operation of a building. Changes in use and operation not reflected in documentation reduce the effectiveness of any actions later relying on it, demonstrating a lack of comprehensive development both during and after building design in BIM environments. Full implementation of standards detailing information to be modelled and exchanged (BSI, 2014) would not address this current issue, instead make it more prominent given the need for skills in managing information in non-traditional formats;

– The contracting out of specific roles reduce the capacity for coordinated approaches to process improvement. Doing so divides responsibility where each constituent

stakeholder or group focusses on their own particular aspect, to the detriment of others in a system contributing to a building's holistic performance. This issue suggests Integrated Porject Delivery (IPD) would be more suited to projects where BIM is implemented as a performance management tool than other methods of building design, delivery and operation; and

– Measuring the effectiveness of BIM as a performance management tool should not focus on the direct application of information stored within, but in the abilities of those responsible for performance management in interfacing with that technology, and the skills necessary for their doing so. Development of skills should also not just focus on the users of information and models to aid in building performance management, but on the designers producing that information.

5.2 Innovation and application of knowledge

The impact this research may have on the subject of BIM and its application to the design and management of building energy performance is outlined in this section. In addition to the subject area, the implications for the industry sponsor and industry in general are also given. Each task detailed in Chapter 4 is indicated in Table 5.1 with its areas of impact indicated. Direct impact is defined as where its contribution may be immediately applicable and is relevant to current practises. Indirect impacts would be applicable given further development throughout the industry as a whole regarding its adoption and implementation of BIM.

Table 5.1: Research tasks and their impact

Task	Industry sponsor	Wider knowledge
Review current state of BIM for building performance management		★
Review the BIM capabilities and adoption strategies of BuroHappold	★	
Develop a standard for the generation and distribution of building performance design information around BIM	★	☆
Create representative models in BIM and EPM tools of an as-built building	★	
Investigate the capacity of building performance data attribution to BIM	★	★
Investigate the performance of the existing building, identifying opportunities for improvement	★	☆
Develop a method for the management of building performance data using design data	★	☆
Identify potential for BIM utilisation in building performance management	★	☆

★: Direct contribution to wider knowledge; ☆: Indirect contribution to wider knowledge

5.2.1 Implications for future use of BIM

Generalisations for the application of BIM to specific areas of design and operation in an industry so varied are bound to hold truth in some areas and be false in others; however, the treatment of information describing buildings as data rather than documents is the

direction in which the industry is moving. With that in mind the following implications may be considered:

– Standardisation of processes to support BIM application will increase its applicability to a wider range of purposes. Shapiro and Varian (2000) suggest standardisation may also reduce the novelty in design of buildings, which is foreseeable, but given the variability between non-domestic buildings and necessity for bespoke engineering solutions, the application of BIMis unlikely to impact variety in any significant way;

– Restrictions on the potential use of information describing a building rely on that information being digitally available*;

– Provision of models as a standard handover practice is not well defined (Alvarez-Romero, 2014), and procedures are not yet in place to provide this information in a format usable by building occupants and operators; however, the recommendations made here demonstrate a potential method of transfer for that information. Existing methods currently not widely employed such as Construction Operations Building information exchange (COBie) demonstrate the gap between ideal and practicable implementation of BIM, where methods of exchanging information are available but are not suitable in some cases given variety between buildings and clients requirements, resulting in inconsistent adoption; and

– The role of the engineer and FM are changing, and the ability to handle data rather than documents is becoming a requirement during both design and management of a building's holistic performance. As such, it should be incorporates into the training for those entering into the AEC industry to support the new data paradigm.

5.2.2   BIM application to building energy performance design

Energy simulation using BIM integrated tools is currently limited to early stage analysis. While continually improving, full evaluation of options and optimisation of services require purpose specific software and expertise. Following the creation and utilisation of models for energy related performance data attribution, the innovations presented in this research have contributed to the subject area by:

– Clarifying the BIM adoption statuses of distinct design disciplines and the reasons for these (Gerrish et al., 2014);

– Identifying that current guidelines for design data management using BIM do not fully account for the specification, creation and categorisation of information describing building performance;

– Providing a framework for the classification of design performance information for its inclusion in a BIM environment (Gerrish et al., 2016c); and

– Defining the capacity of existing BIM data storage frameworks to be attributed time-series performance data (Gerrish et al., 2015).

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*Non-domestic building age data is not available for the UK, but in the USA those constructed before 2006 account for 89% of all non-domestic buildings (U.S. Energy Information Administration, 2012) for which no BIM is available without post-completion modelling.

5.2.3 BIM application to building energy performance management

Building operation utilising BIM and information generated during design is an area under-explored in academic literature. Efforts so far have focussed on the provision of data for FM in the management of assets rather than the building as a holistic entity. The following contributions to the area of BIM application to building operation in the context of its performance management include:

– Demonstration that efficient storage and classification of operational performance is necessary for effective connection with external information platforms;

– Creation of a method for the error removal and analysis of monitored performance data to identify areas of potential performance deficiency (Gerrish et al., 2016b), demonstrating the need for information validation in operational performance monitoring;

– Development of a method for the linking of design BIM incorporating performance information with monitored building energy performance (Section 4.7); and

– Definition of the nature of performance management during operation, identifying the key barriers limiting application of BIM in that process (Gerrish et al., 2017b).

5.2.4 Innovation applicable to the wider industry and sponsor

This research assessed whether BIM could be utilised for building energy performance management, and in doing so developed a prototype demonstrating a potential methodology for achieving this goal in conjunction with holistic evaluation of the processes leading to its application. A method for the extraction of performance information from a BIM environment, and error handling of information collected from a metered building were also developed which could be applied directly to processes the sponsoring organisation currently undertakes. The specific outputs from the research undertaken include:

– Contribution to the BIM adoption strategy throughout the organisation, demonstrating the variable understanding of engineering disciplines and need for holistic implementation across the practice;

– Specification of building performance information to be included in BIM, and the definition of modelling extents to provide EPM with the information it requires (Gerrish et al., 2016c) (specifically relating to UK construction targets as discussed in Section 2.1.1);

– A means of handling mass time-series performance data collected from BMSs, including error-handling, re-sampling and summary, resulting in significant time-savings in processing this data (Section 4.6). This generated lessons learned around how information is being handled and specified at project outset, to benefit later projects and reduce time taken to interpret large time-series datasets in Post-Occupancy Evaluation (POE) activities;

– Demonstration of the potential for BIM application to energy performance management, including visualisation of performance and comparison with design specification (Section 4.7);

– Substantiated evidence of the need for specification adherence following design stage handover (Gerrish et al., 2017b; Gerrish et al., 2017a); and

– Exemplification of BIM capabilities given operational and design performance information in a suitable format (Gerrish et al., 2017b).

Synthesising these contributions to BuroHappold, and using the findings from research undertaken, the following recommendations to the sponsoring organisation are made:

– Provision of information at handover of a building to its occupants will soon require changes in information extent to support information transfer in model-based formats such as IFC and the Autodesk Revit format. Given the widespread adoption of BIM, specification of model-based handover is likely in coming years, including handover of asset information in COBie format, requiring this capability to be developed in conjunction wit the wider BIM adoption strategy;

– The needs of the end-user dictate the extent of information provided, and the condition in which that information is provided dictates the potential for its use in novel, non-standard processes (as demonstrated in this research). BuroHappold must identify at an early stage in the project the information content and extent to be delivered, via the EIR at project outset; and

– Skills required for effective data handling to support BIM and building energy performance information are not those conventionally available as part of engineering education. The engineer's role is changing to adapt to the information infrastructure now required in holistic building modelling, where data creation, utilisation and transfer play a far greater part in the creation of effective design. Skills originally found in data science, database management and programming are becoming relevant to the engineer and technician. Therefore, consideration of the changing design and operation environments supported by data is required during training of those entering related professions.

5.2.5   Contributions to knowledge

Summarising the findings of this research and the implications it has had and will have on BuroHappold and the wider industry, its contributions to wider knowledge around the subjects of BIM and building energy performance management are as follows:

– Focus on BIM as a technology for implementation prompts study of the methods of handling data and creation of new means of translating that information for novel purposes; however, the human aspects of its implementation are being overlooked and remain the largest barrier to effective use outside design environments;

– Standards for information management outside design development do not yet support the application of BIM, resulting in the need for case-specific methodologies that the wider industry can emulate;

– Procedural changes in the development, handover and utilisation of performance information are required to define who is responsible for the maintenance of that information, and that responsibility is currently undefined;

– Use of BIM in building energy performance management relies on too many factors for effective widespread application. Until holistic life-cycle building performance is

considered an integral part of a modelled environment, challenges in implementation reduce potential for its use in that way; and

– The engineer and building operator's archetypal skill-set must change to account for the changing model of building information development and utilisation. Data is becoming the new medium of exchange, and without skills in handling this effectively, the capacity to provide value through its use is reduced.

5.3   Critical evaluation of the research

This section critically appraises the research project, identifying its applicability to the industry sponsor and wider industry, and its limitations.

5.3.1   Research scope

The research undertaken aimed to develop a greater understanding and exploration of the subject, applicable to the wider industry and sponsoring organisation. Though specific solutions were developed for a case-study building, the methods used were platform neutral and generally applicable in other building projects. Findings are also relevant to similar organisations designing non-domestic buildings using BIM technologies; for example, the framework developed in Task 2 (Section 4.3) was applied in the sponsoring organisation but may be applicable to similar industry organisations. The method developed for BIM and BMS connection, while specific to the case-study building, is also relevant to the wider industry following evaluation of its applicability in context with building designers and operators in Task 8 (Section 4.8). Barriers to its wider applicability include the variability of information standards and extent of modelled information from which application of the method could applied without extensive work in preparing that information to the standard required (Section 4.4) from both as-designed and monitored operational data sources.

Upon research commencement, the scope of research was initially broad, aiming to develop a widely applicable tool to management energy performance in a BIM environment. BIMs current application to many aspects of building design and operation suggested a broad approach may be suitable; however, focus was also necessary to identify where development should be made, and how that could best benefit the industry sponsors and subject area. The linear process of sourcing information, evaluating related information describing performance and connecting these generated a prototype methodology, though reflect only a part of BIMs potential to influence the wider process of building energy performance management.

5.3.2   Research process

Progression through the framework proposed during the initial research and subject exploration (Chapter 2) involved slight variation to that process, responding to challenges in accessing information and changing technologies available to handling that information. To ensure findings for each research task were based on a clearly defined methodology, a review of the literature related was undertaken contextualising that task. As such, the

rapidly developing field of BIM modified planned research tasks to incorporate changes in technologies (for example, the opening up of modelling tools Application Programming Interfaces (APIs) to support interaction with embedded data) during development of the prototype method for BIM performance linking (Section 4.7).

Several pieces of work not published or included here formed the development of skills necessary to the research process, learning how to implement the technologies and tools available through trial and error. For example, the choice of JavaScript Object Notation (JSON) as a lightweight format for BIM data transfer originated from testing a web-based platform for interfacing with that data; however, given time and capability constraints, an alternative method was chosen.

5.3.3 Validity and application

The case-study approach and wide variability across the AEC industry means generalisation of research findings is difficult. The findings presented here are based on research methods developed with consideration of their applicability to the processes being examined, with those methods employed to generate widely applicable findings, while benefiting the industry sponsor. Triangulation was used to combine numerous means of conclusion in the tasks to address the potential deficiencies of a single approach and increase findings relevance to industry and non case-study buildings.

Reliability of the data used is dependent on the systems in place recording that data describing the building being monitored; however, the processes utilising that information presented here may be applied to other non-domestic buildings and are not specific to the case-study. The following issues were noted with the data collected here:

– Data collected from the case-study buildings BMS was processed to remove errors, potentially reducing its accuracy;
– Spatial performance attributes may not be attributed to the correct spaces in the tool demonstrating a BIM and performance data link due to the BMSs lack of structure at data extraction; however, this would not impact findings;
– Where interviews were used, care was taken to sample those broadly representative of the roles represented; and
– The changeable design environment in which BIM is applied means replication of the processes detailed here on other projects may be difficult. However, care was taken to avoid specification of methodologies relevant only to the project being used as a case-study, and conclusions made relevant to the wider construction industry.

5.4 Recommendations for further research

Based on the research findings, limitations and conclusions, the following suggestions for future research are submitted to the industry sponsor and wider industry. Several opportunities to build upon this research are also presented, using the findings from this thesis and developing technologies in the field of BIM for building performance management:

– Disproportionate capabilities shared across design disciplines can reduce the quality

of BIM delivered. Further research is required on the capability of designers and their impact on delivering information in formats usable by downstream stakeholders for use in optimising energy performance;

– The scalability of the prototype methodology to other buildings and modelling and metering platforms needs to be investigated, defining a more commonly applicable process in which this method could be applied to other buildings;

– Further study is required to determine how design stakeholders can effectively contribute to the process presented and their role in delivering information suitable for building operators;

– The quality and content of models developed in BIM environments establish their suitability for further design development and utilisation. Further research may be applied to the impact information standards have outside the design environment on the informations end-user;

– Responsibility for the commissioning of systems required for the interpretation of building energy performance is made unclear through sub-contracting individual parts of a holistic process. Further work should be done to examine the impact BIM is having on the complex relationships and responsibilities in the upkeep of information describing systems and performance, including operational monitoring and BMS interoperability;

– Further research is required into the semantic data-models necessary for the handling of monitored performance data and quality of that information;

– Currently the prototype method demonstrated shows a one-way link from BIM for use in FM activities; however, a two-way link could be possible given training of FM and building operators in updating a model to correspond with changes in the building's life-cycle. Original research studies should include the testing of a model upkeep process using manual or automated means during building operation; and

– Further research into the connection between handover information and its accessibility by building operators and occupants is required to identify the influence these may have on the occupant and their behaviour in line with PAS 1192-3 (BSI, 2014).

More broadly, the potential for feeding back experiences from those utilising BIM following handover of design models and performance specifications must be investigated further, to identify how best to implement it effectively in context with those responsible for its application. Closing the loop between design and operation remains a key challenge throughout the AEC industry, contributing to the performance gap (Section 2.2), to which ensuring lessons are learned from projects and experiences is essential to promote and develop upon previous projects. Paranagamage et al. (2012) identified that lessons learned approaches aim to avoid repetition of past mistakes, ensuring past successes are replicated and to encourage innovation. It may also be prudent to state that education of new and experienced stakeholders in construction design and operation processes, play a large part in encouraging innovation and utilisation of those lessons, to further current and future capabilities. Linking lessons learned to education of the collective stakeholders in the AEC industry is another area which would benefit from further research. encourage innovation.

5.5   Conclusion

The aim of this research was to explore the effectiveness of BIM as a supporting factor in the management of information describing buildings in-use performance, utilising monitored and design data to develop a method for linking these domains. The research has shown that while possible, the technological, methodological and skills-based barriers preventing widespread adoption of BIM in operational building energy performance management are significant. Industry adoption of BIM as a standard working process and platform about which to develop building designs, provides the opportunity for vast amounts of information to be made available to the occupants of building post-construction and handover. These data-rich environments in conjunction with monitored data could potentially replace a conventionally specified BMS as the performance management method; but several factors must be addressed before this could become a reality.

Mandated BIM implementation is addressing its slow adoption rate but the effects will not be seen for several years given the industry's protracted lead times. Adopting BIM as a standard design development platform does not currently support effective multi-disciplinary processes. Until it does, methods of transferring information between purpose specific tools is the most effective method of concurrent design development, incorporating performance optimisation during design.

New methods of interfacing with information stored in a BIM environment as data, rather than modelled objects are becoming available. These create greater opportunities for design optimisation, and open previously inaccessible data environments to a wider range of engineering disciplines. As such, utilisation of these for novel purposes will increase, potentially supporting areas outside design, such as building operation. Findings have identified potential issues with monitored building performance information. Identifying these and enabling measured performance to be trusted is the first step in creating a dataset representative of a building's performance, for its interpretation and analysis either manually or automatically. Integration with other data environments can then be attempted, but without error removal measures, the applicability of any system is limited by the accuracy of the information it utilises.

This research has demonstrated that the application of BIM to performance management is an area where further research and development must occur for a widely applicable means of implementing BIM as a performance management tool to be possible. For the first time, a process oriented approach, examining the systems in place throughout design, handover and operation have been considered alongside the technological application of BIM in this way. Through development of the prototype tool and methodology, it has outlined the potential for BIM use as an information aggregate, demonstrating its role as a storage medium, information transfer mechanism and supporting tool in performance management.

Changes in engineering design and building operation processes must be made to adapt to the new data-centric environment, in which the building is no longer a physical entity described by digital documentation, but a combination of digital and physical information of which effective management is essential. The effectiveness of BIM as a technology relies on the tools used in handling building information and their capabilities. Whereas the effectiveness of BIM as a process is determined by the methods used, and the abilities of those working with that technology to utilise it effectively.

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A Paper 1

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Cross discipline knowledge transfer for concurrent BIM adoption in an engineering organisation

T. Gerrish, K. Ruikar, M. Cook

The use of Building Information Modelling (BIM) in the design environment has been widely discussed within the field of construction. However, its effective use requires that all contributing designers meet the technical capabilities necessary to use this environment. A reliable development process utilising BIM to its full potential requires concurrent advancement of multiple disciplines working collaboratively. An investigation into how different disciplines are advancing their BIM capabilities within a multidisciplinary engineering consultancy is carried out to identify where improvements in this process may be made. New technology and process implementation are discussed and the construction industry's silo mentality is identified as a significant factor impacting this. The consultancy's BIM capability is evaluated through semi-structured interviews with discipline representatives involved in its implementation, outlining their experiences with implementation so far, and highlighting opportunities for greater knowledge transfer. Building Services and Physics were found to require most development as a result of the complexity of modelling within these disciplines and the lack of projects involving all disciplines equally. Other disciplines were found to be more BIM capable, but these capabilities are often lowered due to reliance on external stakeholders. This study contributes to the justification of BIM implementation within building design development and identifies the need for more effective adoption across the industry as a whole, not just within discrete areas.

A.1   Introduction

Building Information Modelling (BIM) is currently being implemented throughout the construction industry worldwide. In the context of this paper, BIM refers to the collaborative working environment facilitated by developments in technology to support the concurrent contribution to construction projects during their design phase. UK government targets for BIM are due to be enforced in 2016 (Cabinet Office, 2011), and the construction industry requires vast changes to its practises and cross-disciplinary processes for these targets to be met. Adopting new practises is challenging, and the identification of key areas impacted by implementation is the first step towards facilitating a more effective transition to new working practices. The Architecture, Engineering and Construction (AEC) industry is slow to adopt new working practises, and though the identification of the need to do has been made clear (Egan et al., 1998), these changes have not been as forthcoming as previously hoped. This is confounded in BIM implementation where the entire industry is impacted by its adoption.

This paper investigates how a multidisciplinary engineering consultancy currently uses BIM, exploring its cross-discipline capabilities, to determine opportunities for a more effective implementation strategy. The objectives of study are defined as the identification of drivers for change bringing about implementation of BIM as standard practise, definition

of the barriers to effective implementation, evaluation of the organisations current capability (establishing shortcomings of its BIM implementation) and redefinition of the organisation's framework for BIM adoption as a collaborative working tool.

This forms the early stage of a larger Engineering Doctorate (EngD) study investigating the use of BIM as a life-cycle building performance management tool, requiring the design team to input performance-impacting parameters into a BIM model for later extraction and use. Prior to this capability, the design stakeholder must first understand the impact of their actions on the holistic design process, leading to eventual building operations.

A.2 Research justification

A.2.1 Slow rates of adoption

Adoption of new technologies and processes in the AEC industry is often hindered by complex relationships between stakeholders affiliated with a project (Hosseini et al., 2013). Each has their own agenda and sometimes incompatible processes hindering cross discipline collaboration. This is confounded by the difficulties faced when operating in a collaborative working environment, where a legal framework governing the responsibilities and liabilities of all parties involved has yet to be fully defined. The industry as a whole understands its need to improve the way it works, using "lessons learned" systems to assist in the amendment of operations (Mitra and Tan, 2012). Collaborative working and interoperability have become buzz-words that show to other practitioners that an organisation has recognised its need to be more effective in the work it undertakes (Ilich et al., 2006); however, their meanings lost amongst the ease of maintaining existing practises.

A.2.2 Drivers for BIM adoption within the AEC industry

While market needs maybe considered the overall driver for change within a certain industry, ultimately the local government states the requirements that industry must meet. The Egan Report (1998) proposed aspirational targets to implement industry wide changes to processes in order to remain globally competitive. The government BIM agenda (BIM Task Group, 2011) informed by these reports requires "*fully collaborative 3D BIM (with all project and asset information, documentation and data being electronic) as a minimum by 2016*".

Industry support for the implementation of BIM is widespread, with the RIBA (2013) Plan of Works, (the principle framework for project development management in the UK) recently revised to include BIM processes. However useful, industry initiatives provide guidance by which to develop BIM capabilities, but include little instruction in how to implement it in project settings or across entire organisations.

The organisations governed by industry standards and government regulation experience the benefits of BIM implementation (Liu et al., 2010), driving the organisational agenda put forward by its leadership team, and are representative of the driving factors of a typical multidisciplinary engineering organisation. The organisation assessed in this paper states its goals to be "*making BIM the default approach to building modelling and the production*
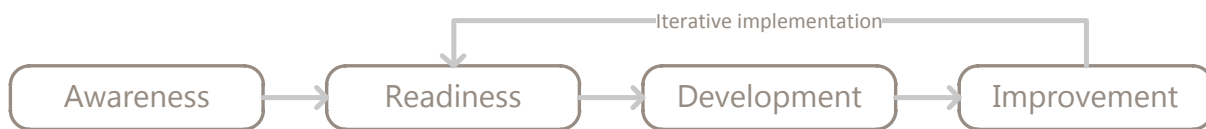
Figure A.1: Iterative improvement cycle

of construction information" in order to increase efficiency and productivity and "*develop common standards across regions and disciplines to enable widespread adoption of the most effective techniques*". Successful adoption of a change in industry processes can be described using an iterative improvement cycle (Fig. A.1), showing that prior to change readiness, awareness needs to be attained. In stating its own targets, the organisation has taken the first steps towards deployment and improvement.

Disciplines within an organisation are subject to that organisations governance, but are more reliant on its constituent individual's agenda. Within the organisation studied here, the capability each discipline performs at is unavoidably different, each developing their own capacity, specialising in distinct areas where the interoperability with other areas is an afterthought to the development of discipline specific standards. An ideal design environment would link all areas of development to bridge the silo developments, facilitating fully collaborative design and construction processes, where information is shared; however, this is still unobtainable given current industry legal and technological frameworks. Arayici et al. (2011) suggest that careful consideration of individual experience can improve change adoption success by facilitating a bottom-up approach from within the organisation. This suggests that change adoption becomes a driver in itself, with innovation in one area spurring the implementation of new processes and techniques in another to meet the more efficient concurrent practises.

A.2.3   Factors affecting successful change implementation

The successful implementation of new methods of work requiring consideration of people, processes and technology is well documented (Gu and London, 2010; Stephenson and Blaza, 2001). Some have suggested that it would be advantageous to include management in these elements to include changes to the structure governing these (Ruikar et al., 2005). Each of these elements are applied to the case study organisation to ascertain factors limiting its current adoption strategies.

Automation of inefficient practises will not yield a more efficient work process. Management of change is required to coordinate an entire organisation, and exists to consistently evaluate operations. Delegation of responsibility into hierarchical management systems and chains of command is necessitated by the convoluted working processes that organisations have developed (Josserand et al., 2006), and endorsement of systems and careful management of individual resistances can reduce many problems from the bottom up.

Processes define the way a certain task is completed and govern the interactions through which internal and external stakeholders contribute to a project's goal. Within the organisation assessed here, these have changed little over recent years, except for partial automation. New processes need to be developed alongside technology adoption (Raineri, 2011), and existing processes must be rationalised with this reasoning supported

by economic or efficiency gains. Attaran (2004) reasons that failure to identify ineffective processes almost guarantees an unsuccessful transition, potentially wasting resources improving a process with no reason to exist otherwise.

Individual resistance to change has been identified by several authors as a common hurdle to overcome when adopting changes (Gonçalves and Gonçalves, 2012; Henderson and Ruikar, 2010), and arises as a result of several factors. These could be previously negative association with change adoption, or lack of perceived obligation to implementing such change.

Technological capabilities define the capacity to adopt new technology, especially for integration with legacy systems. Whilst easily met given the requirements for basic BIM implementation, the entire organisation needs to be able to access and use tools at an equivalent level of capability paralleled with its surrounding stakeholders. Concurrent access and contribution to a project by several stakeholders requires each contributor to work to common and agreed upon standards. Interoperability is slowed through incompatible systems, and the slowest link in the process is the one dictating the maximum rate of output (Pala et al., 2012).

In addition to those described previously, factors such as product suppliers, specialist contractors and industry contemporaries outside the organisation have a large part to play in pushing and obstructing change. In the case study organisation, each discipline can work as separate units away from each other in order to carry out roles in different projects, but change implementation in each varies with influences from the discipline in which it occurs. External factors are especially impacting in the AEC industry, which requires collaboration between several partners in the delivery of complex projects, where the behaviour and requirements of one party affects the way that another works and contributes.

A.2.4   Silo mentality

Fragmented approaches towards innovation and development within the construction sector are often attributed to its silo mentality (Froese, 2010), suggesting that concurrent development across all disciplines would lead to a more effective adoption strategy for new processes and technologies. In the context of project management, an engineering design may be considered a multi-project environment, involving different disciplines, each adhering to their own industry standards. In complex multi-project environments, the ability of a project manager to oversee development in all areas concurrently is limited (Patanakul and Milosevic, 2009), requiring delegation of oversight, and overlooking collective collaboration in favour of silo development.

Elonen and Artto (2003) go into detail, investigating the problems that multi-project environments can face and citing inadequate competencies at a project level and poor management of project-oriented business as significant problem areas, reducing overall capability. Within the AEC industry, Murphy et al. (2011) suggest that limited capability of project stakeholders plays a large part in constraining innovation and overall competency, furthering previous findings by Zou et al. (2007) in construction project environments. Sharing information between different disciplines offers the opportunity to implement new process/technology adoption (Arayici et al., 2011) as well as encourage the cross-discipline collaboration required to make BIM work.

A.2.5 Summary

For life-cycle BIM to be feasible, the capabilities in all BIM-based design contributing areas need to be consistent and equal. Sustainable building design is grounded in holistic design environments, where contributors to the design understand the needs and reasons behind others decisions. Synchronised project development may mean that the capability of one party to improve performance can be overlooked as a result of their incapability to contribute at the same rate as others. Using lessons from one discipline already using BIM in another at a lower level of implementation may improve the adoption rate through the pre-identification of potential pitfalls and problems that must be overcome.

A.3 Methodology
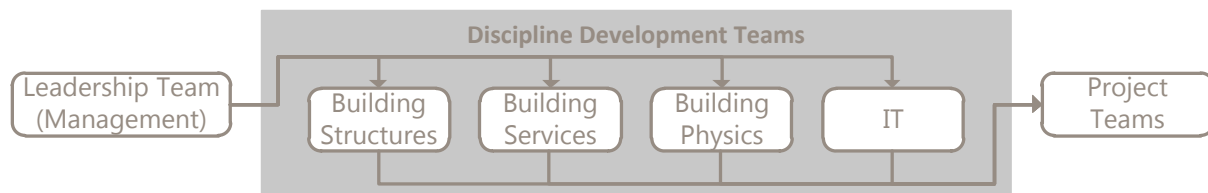
Figure A.2: Organisation BIM implementation maturity teams structure

The organisation assessed in this paper contains disciplines operating both separately and collaboratively across a range of AEC projects. Its BIM capability is assessed following a two part investigation looking at project-based BIM implementation, and responses from semi-structured interviews with representatives of the organisations constituent disciplines describing their experiences in using BIM. The implementation structure for the organisation assessed within this paper is shown in Fig. A.2, enforced by a leadership team to which each discipline reports, while comprised of project teams.

A.3.1 Project-based BIM implementation

The first investigation scored exemplar projects according to their use of BIM concepts, technologies and processes against criteria defined in the NIBS (2007) Interactive Capability Maturity Model. Capability and maturity may seem interchangeable in the context of BIM implementation, but have different definitions (Succar et al., 2012). Capability describes the ability to perform a specific task or function, whereas maturity is the degree to which that capability is implemented.

Four single discipline projects were identified for evaluation from the "Structures" and "Building Services" disciplines (a skewed representation of the whole organisations capabilities, but proportional to the make-up of the implementation teams). Results of this assessment are shown in Table A.1.

While limited, the conclusions that may be drawn from this preliminary investigation are that representation of "Structures" in the development teams is greater than that of other disciplines, and representative of the BIM maturity shown. Organisational maturity is greater than team maturity including external stakeholders; where lack of capability

Table A.1: Project-based BIM implementation results

	Structures			Building Services	Average
Modelled data intelligence	3	2	2	2	2.25
Interoperability	2	2	1	1	1.50
Data exchange	2	1	1	1	1.25
Workflow	1	0	1	1	0.75
Cost data	1	1	1	1	1.00
Time data	0	0	0	0	0.00
Spatial location	2	2	2	1	1.75
Life-cycle	0	0	0	0	0.00
Customer involvement	2	1	1	1	1.25
Organisation Score	1.75	1.50	1.25	1.25	1.44
Team Score	0.90	0.60	0.60	0.60	0.68

from outside the organisation holds back the team charged with delivering that project. In addition, limited project scope reduces the ability of the team to meet a level of maturity that is not required of them. These findings were used to guide the targeted questioning used in the later interviews and help identify the limitations currently encountered when using BIM during design development.

A.3.2   Semi-structured interviews

Interviews with representatives involved in BIM development and application within the "Structures", "Building Services" and "Building Physics" disciplines were conducted, in addition to representatives of the "Management" team overseeing this, and the "IT" team implementing any system changes to necessary to facilitate them (see Table A.2). Interview structure was based around four areas: the role of the respondent, their perceived discipline BIM capability, how they work with other disciplines within and outside the organisation and what they perceive to be the biggest barrier to overcome to move forward.

Table A.2: Interviewee roles and disciplines

Interviewee	Role/Discipline
A	Structural Technician
B	Systems Analyst (IT)
C	CAD & BIM Manager (Building Services)
D	Building Services Technician
E	Building Physicist
F	Project Principal (Management)

Understanding the organisation as it currently operates and identifying potential areas for improvement requires an opportunity for the interviewee to explain their reasoning. Respondent familiarity with the subject area is essential for an accurate portrayal of current implementation (Cresswell, 2008), and those interviewed are members of the discipline development teams (Fig. A.2) meaning their understanding and experiences implementing BIM are established.

A.4   Interview analysis

Thematic content analysis was used to categorize commonly encountered issues based on the NIBS (2007) categories. From these, common issues causing problems in implementing BIM throughout design development and across the organisation are identified, indicating the interviewee disciplines supporting these issues.

Collaboration

Interviewees A-D used the government definition of BIM, though all stated this was limited and BIM constitutes a number of definitions, primarily a process or series of processes more than a technology, indicating that individuals are prepared to experience reduction in efficiency prior to full implementation. Several respondents mentioned that general understanding of BIM by those not directly involved in its implementation was limited. While not impeding implementation, it highlights to need for the organisation to gain a thorough understanding of BIM as a concept rather than a technology.

Interviewee B identified that knowledge sharing between disciplines should be a forefront issue in BIM implementation, noting that the discipline divide often causes collaboration problems within small, non-integrated projects. In a project based environment the silo-mentality that forms between project teams and within discipline groups needs to be overcome for fundamental change to happen, where the goal of the teams should be to further overall capability and replicate beneficial developments made in one area across the organisation. Bosch-Sijtsema and Postma (2006) reason that innovation and development centred on a single project was difficult to distribute throughout the rest of the organisation and requires the support of all members of that organisation to transfer, echoing Interviewee B's point and suggesting that whole-project based environments advance process optimisation rather than innovation.

Several respondents mentioned the limited scope of collaborative works that should be prioritised during early design stages (Interviewees A & D). Interviewee D went on to enforce the notion that collaboration with less capable stakeholders can reduce overall design development due to their lack of competency (Interviewee D).

Information transfer

Complexity of modelling for different purposes was perceived as too great for current BIM tools to manage (Interviewees A & E), with the scope for BIM integrated performance analysis (structural, energy, operations, maintenance etc.) resulting in common formats being unlikely to be developed, (Interviewee D). However, Interviewee B noted the possibility of using BIM as an information repository rather than a design/analysis tool, instead of the conventional industry norms of project extranets. Before this can be achieved, Interviewee C suggested that supply chain segregation preventing the effective gathering and storage of information for input into BIM environment would need to be overcome.

Standards & interoperability

The use of proprietary formats within disciplines limit interoperability, resulting in additional work translating information (Interviewee A & F), but are required for discipline specific processes. Industry bodies specifying standards produce concurrent frameworks for implementation, but supply no integrated guide between themselves for use throughout the industry (Interviewee D). In-house standards will eventually overcome such limitations, e.g. standardised objects for use in multi-discipline models, but for expansive subjects such as building services, considerable work is required in developing these (Interviewee B).

Future capabilities

Interviewee F complained that resources allocated to BIM implementation and development were not being used successfully. Smith and Tardif (2009) identified ineffective resource use as a significant way that implementation is hindered within organisations. Interviewee D highlights that technological and process advancements take time to implement due to project length, requiring significant foresight by those overseeing change. Every discipline within the organisation is subject to this constraint and as a result, familiarity with existing processes can make alternative solutions seem more uncertain in comparison (Ford and Garvin, 2009).

Knowledge transfer

Silo mentality is also apparent within the organisation, where development is limited to the development team with that purpose, and whose work is only noticed by other members of that team (Interviewee F). Better use of in-house knowledge and resources contributing to process improvements would benefit the entire organisation, not just the team that benefits locally. Interviewee C suggested that all members of project teams need to understand what is required of them and use the capabilities of other stakeholders to develop their own skills, but that some disciplines would require more disproportionate input from others.

A.5   Conclusions
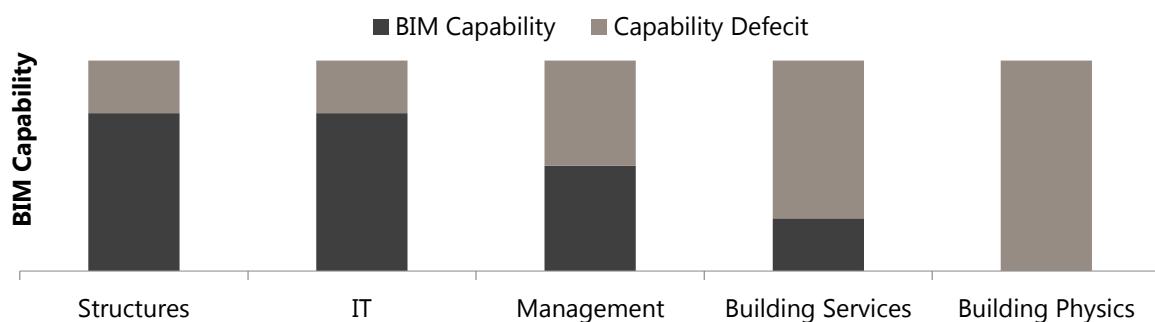
Figure A.3: Relative discipline BIM capability levels

Individual discipline capability varies, but is underpinned by a well-established "IT" infrastructure capable of change. "Management" requires more support to buy in fully to the idea of BIM as an efficiency improving process, while "Building Services" require the majority of work to meet the government targets. "Building Physics" currently has little interaction with other disciplines using BIM tools or processes, but foresees the benefits that could come with it as an information storage repository. Fig. A.3 indicates each disciplines current relative performance, but this does not account for project variation such as external stakeholder capability limitations and the availability of resources and training in BIM tools and processes.

Recommendations for the improvement of BIM implementation within the organisation, also applicable to other similar industry practitioners, are that following standard processes at project onset would enable much faster progression than developing those processes in each project. Shared tools such as common object libraries and methods of exchanging files reduce unnecessary rework and improve progress effectiveness; however, these must be supported by those contributing to, and using them. This requires all project members to commit to a standard of practice at project onset. A recurring theme throughout this investigation was of the least capable stakeholder lowering the capability of entire project teams. A common standard of ability should not just be expected within the organisation, but with external collaborators, whose commitment to a common standard can reduce rework, slowdown and error. Skill sharing between disciplines outside of collaborative projects should be more prevalent within the organisation. It is evident that in organisations where each discipline has its own specific projects, opportunities for this knowledge transfer are limited; however, BIM is changing the design environment, affecting all members of the organisation. It would therefore be beneficial for all employees to understand what is expected of them once it is part of standard practises.

A.6 Future work

Drawing from lessons learned during this investigation, further research will be performed on the implementation of cross disciplinary information sharing using BIM between building energy performance simulation, and the design of building systems requiring input from these simulations. Research related to performance management of buildings using this BIM embedded data will also be performed.

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B   Paper 2

Gerrish, T., Ruikar, K., Cook, M. J., Johnson, M., and Phillip, M. (2017). *Using BIM capabilities to improve existing building energy modelling practices.* In: Engineering, Construction and Architectural Management 24 (2). DOI: 10.1108/ECAM-11-2015-0181.

Using BIM capabilities to improve existing building energy modelling practices

T. Gerrish, K. Ruikar, M. Cook, M. Johnson, M. Phillip

Purpose – This paper presents a review of the implications Building Information Modelling (BIM) is having on the Building Energy Modelling (BEM) and design of buildings. It addresses the issues surrounding exchange of information throughout the design process, and where BIM may be useful in contributing to effective design progression and information availability.

Design/methodology/approach – Through review of current design procedures and examination of the concurrency between architectural and thermophysical design modelling, a procedure for information generation relevant to design stakeholders is created, and applied to a high-performance building project currently under development.

Findings – The extents of information key to the successful design of a building's energy performance in relation to its architectural objectives are given, with indication of the Level of Development (LOD) required at each stage of the design process.

Practical Implications – BIM offers an extensible medium for parametric information storage, and its implementation in design development suggests the capability for inclusion of building performance data integration. The extent of information required for accurate BEM at stages of a building's design is defined to assist comprehensive recording of performance information in a BIM environment.

Originality/value – This paper contributes to the discussion around the integration of concurrent design procedures and a Common Data Environment (CDE). It presents a framework for the creation and dissemination of information during design, exemplifies this on a real building project and evaluates the barriers experienced in successful implementation.

Keywords – BIM, BEM, Design and development, Stakeholders, Information exchange, LOD

Paper Type – Research Paper

B.1   Introduction

The design of a building is a major determinant in its operational energy performance, with decisions made at this stage contributing to the energy consumed during use (Bordass et al., 2004). Widespread adoption of Building Information Modelling (BIM) to support design provides a platform on which improvement of this performance could be made (Krygiel and Nies, 2008). Through creating a shared knowledge resource for descriptive information, forming a reliable basis for decisions during its life-cycle (BIM Task Group, 2011), BIM could provide the means to transfer information more effectively than the multiple formats and channels previously employed (Chen and Luo, 2014; Redmond et al., 2012; Titus and Bröchner, 2004).

Building Energy Modelling (BEM) is the analysis of building energy performance through its simulation, using predefined criteria describing building composition and utilisation. McGraw Hill Construction (2010) identified the growing benefits of BIM

enhanced BEM through numerous case studies and industry feedback, showing how the transfer of information between BEM tools and BIM authoring tools can facilitate the design of more sustainable buildings. Unfortunately, the quantification of improvement is a difficult metric to measure, given each projects uniqueness. However, increased efficiency in modelling processes (re-use of information from a Common Data Environment (CDE)) enables more time for performance analysis and design optimisation (Arayici et al., 2011).

Understanding the parameters necessary to enable multiple users to complete design activities is essential in the use of BIM, with limitations on accuracy imposed by the extent and detail of modelled data across various modelling platforms (Menezes et al., 2012; Bordass et al., 2004). Information availability also changes throughout the design process – and can only be comprehensive post-construction. Bazjanac and Kiviniemi (2007) demonstrate that data exchange requires translation of datasets to support downstream applications, and that simplification is often used to enable this transfer. Tribelsky and Sacks (2010) action pathway identifies information flows and suggests BIM could assist in identifying the points at which design relies on exchange of key data. However, to implement process efficiency improvements, uncertainty at the points of information redistribution must be mitigated. Collection of information in a structured environment (such as the data drop concept (BIM Task Group, 2012)) allows incremental validation and extraction of descriptive data at these points, for input into BEM environments.

This work aims to identify the current capacity of BIM in the handling of BEM data, how information moves between these two areas, and how procedures must change to enable effective use of these two modelling platforms concurrently, where full interoperability is not yet realised. The BEM design process is mapped alongside an engineering design process, indicating the stakeholders involved at each stage of development. The parameters required during these stages are recorded in a BIM environment where a process map including fixed data-drop points is defined.

The BIM environment discussed in this research refers to Autodesk Revit and its capabilities as a 3D modelling tool with attached databases. However, it must be stated that the BIM environment is more than data developed in a single software platform and represents the sum total information developed throughout a building's design.

B.2   Background

The construction industry is known to be comprised of silos of contributing designers with periodic coordination and information sharing (Gelder, 2012; Merschbrock, 2012). These dis-integrated silos have resulted in the separate development of discipline specific modelling tools for specific design purposes. For example, Autodesk Revit for creation of architectural layouts and drawings, IES-VE for creation of energy performance simulations, and numerous other tools dedicated to one particular aspect of a building's design or eventual operation. Transfer of information between these tools relies on the ability of each tool interpret the others output, utilise this data and record this in an interpretable format.

Methods of sharing information between BEM and BIM tools have emerged in the form of exchange formats, aiming to provide an open environment in which extensible data can be recorded in a non-proprietary format (Laakso and Kiviniemi, 2012). Proprietary

tools then access this information and in most cases write to the same open format for sharing with other tools. However, given the availability of an open format to all potential authoring and reading environment, some loss of functionality is often experienced as these proprietary tools have specific functionality not represented in open exchange format (Fig. B.1).
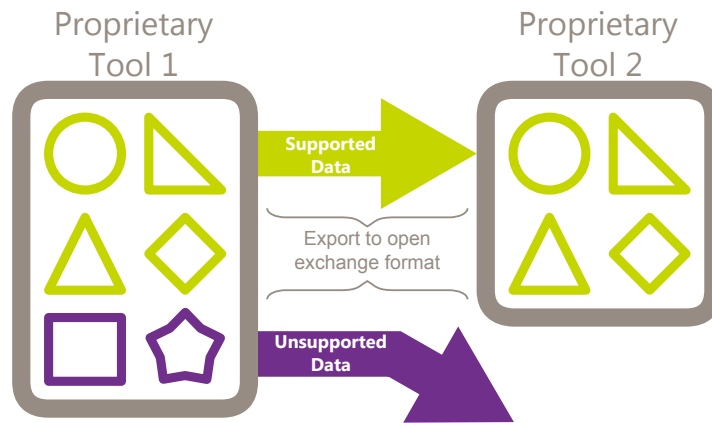
Figure B.1: Loss of data integrity/accuracy through export via open exchange formats

Sacks et al. (2005) suggest error reduction could reduce whole project cost by up to 4.2%, with reduction of rework constituting a significant proportion of this (Hwang et al., 2009). As the building is developed and occupied, the amount of related information increases, as does the likelihood for inclusion of inaccurate data (which has been superseded or incorrectly recorded). Hicks (2007) expanded upon this problem, stating waste occurring from inaccurate information could result in inappropriate downstream activities, corrective actions or additional verification, with Love et al. (2011) suggesting errors are an unavoidable event using BIM.

Given the cumulative amount of data generated in a construction project (Tribelsky and Sacks, 2010) and the number of stakeholders involved (Hughes and Murdoch, 2001), identification of the key data necessary to support concurrent and downstream engineering activities is essential. Research into information transfer has thus far concentrated on whole project aspects such as transfer methods (Tribelsky and Sacks, 2010), operation efficiency (Titus and Bröchner, 2004) and stakeholder interactions (Olander and Landin, 2005), without definition of the types of information required for a singular aspect of design. For the design of a building's energy performance, creation of an information development and verification framework could reduce the likelihood of inaccurate information being used and recorded at key stages of project development.

B.2.1 Interoperability between BIM and BEM

Several studies have attempted to incorporate information storage (BIM) and performance analysis (BEM) functionality (Table B.1), but encounter recurring limitations, most commonly during information transfer between BIM and BEM. Information is currently stored in separate formats before interpretation (Hitchcock and Wong, 2011), with BIM and BEM developed separately, allowing non-concurrent changes to appear, and contributing to the performance disparity between predicted and post-construction building performance.

Additionally, transfer of information using a common format is rarely used. For example, storage of Heating, Ventilation and Air-Conditioning (HVAC) systems details or spatial geometries is possible in both BEM and BIM tools, however the method of storing this information is not standardised leading to incompatible transfer of this data.

Table B.1: BIM integrated energy assessment/design studies

Author/s	Technical Barriers
(Leicht and Messner, 2007)	User error
	Information extent not defined
	Uncertain required modelled aspects
	Work duplication in transition between traditional and BIM systems
(Azhar et al., 2009)	Value/cost regarded more commonly over building performance
	Energy assessment not completed between detailed specification and build completion
(Schlueter and Thesseling, 2009)	External parameter storage easier than use of a BIM environment
(Hjelseth, 2010)	Information not considered an asset and therefore not requested
	Little guidance available for information relevance
	Input information only benefits the receiver, not the producer
(Aksamija et al., 2011)	Significant software customisation required
	Multi-stepped processes susceptible to user error
(Corry et al., 2011)	Design intent lost post-completion and commissioning
(Welle et al., 2011)	Long model preparation times
	Inaccurate and inconsistent data conversion
	Missing data
	Inconsistent analysis results (metrics, coordination)
(Sanguinetti et al., 2012)	Separation of building models and analysis model during design
	Data access restricted by storage format
(Aziz et al., 2012)	Changes in design resulting in incorrect representative models
(Sinha et al., 2013)	Current energy analysis plug-ins within BIM software based on simplified consumption estimation
	No current definition of embedded BEM parameters within a BIM environment
(Costa et al., 2013)	IFC exchange format is the "*lowest common denominator*" limiting functionality

Building energy modelling

During building design, simulation is widely used to inform decisions governing a building's performance (such as the sizing of plant equipment and provision of services). Discretisation of design aspects (for example, simplification of external climate or factors applied to fixed equipment performance values to account for changes in utilisation over time) are required to simulate performance (Clarke, 2001, p. 64). The various purposes and methodologies of BEM add further complexity to determining a reasonable level of input detail to output valid results.

BIM parametric information storage and utilisation

Autodesks Revit offers a form of simplified energy performance analysis (Green Building Studio), estimating whole building performance. This is useful at early stages of design

for comparison between options, but later where calibration of operating schedules and definition of equipment loads is essential, a validated analysis tool is necessary (Ryan and Sanquist, 2012).

Several efforts to integrate BEM within BIM (or using BIM data) have been attempted (Hitchcock and Wong, 2011; Azhar et al., 2009; Bazjanac, 2008), with Aksamija et al. (2011) and Sinha et al. (2013) demonstrating how use of BIM for compliance checking and basic sustainability analysis can be achieved. However, performance analysis integration is still undeveloped and the information from the BIM must be extracted or copied, then evaluated separately.

Interoperability

Information sharing between BIM authoring tools and BEM tools currently relies on the open exchange formats Industry Foundation Class (IFC) and Green Building Extensible Mark-up Language (gbXML). Both provide means of storing geometry with attributed data; however, this information is often not accurately exported by the BIM tool or interpretable by the BEM tool. Fig. B.2 demonstrates this through creation and transfer of information between Autodesk Revit and IES-VE via the gbXML and IFC formats.
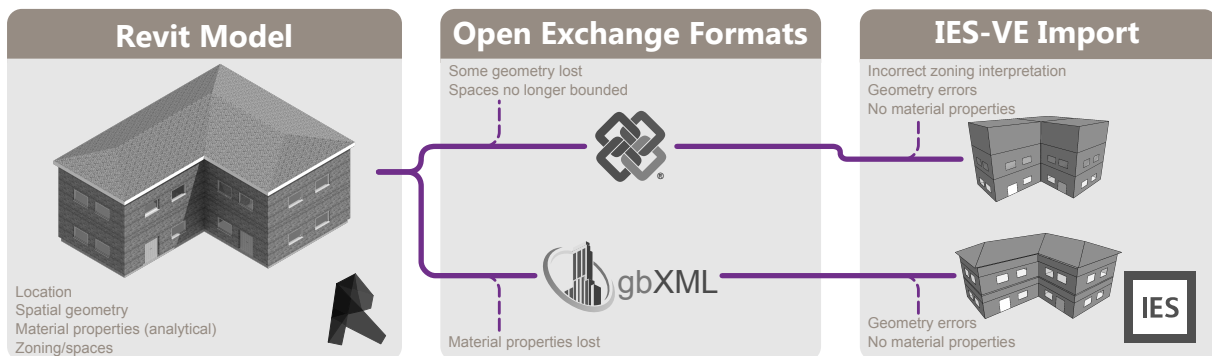
Figure B.2: Data loss from file creation and interpretation

This indicates that a specification for storage of performance impacting parameters is required (building on work by Morrissey et al. (2004)) outside attempts to enable this through open exchange formats, enabling accurate information transfer between energy modellers and building designers.

Process mapping of BEM during building design has been investigated previously (Attia et al., 2013; Grinberg and Rendek, 2013). Comprehensive guidance in the implementation of integrated energy design given by Intelligent Energy Europe (2007) did not include reference to implementation within an integrated design/analysis environment (BIM). However, it did define the process of BEM and indicated the problems encountered in attempting to streamline this process. For example, the additional time and resources required during early design, and the need for all stakeholders to appreciate the impacts of theirs and others actions in the overall design process.

B.3   Methodology

This paper proposes that BIM may be a repository for information storage and accuracy checking during design, to produce an as-built building model, used for BEM interim to the implementation of open exchange formats. The reasons described previously form the basis for the creation of a procedure followed to enable accurate information storage and transfer between a BIM environment and BEM, using conventional means supported by a defined extent of data being shared.

The methodology used to infer conclusions regarding the potential for implementation of a BIM/BEM information generation and access framework was developed during the design of several key projects, where both BIM and BEM were used concurrently, feeding into the finished design. The procedure used is described in detail in the following section, with an overview of this process, and the means through which conclusions were drawn are given here.

B.3.1   Building performance design information

Initially, identification of the information pertinent to the development of an energy model at different stages of design is made. The extents of this inform the information extracted from the BIM at progressive stages of the building design development process. The BuildingSMART model view definition for Architectural Design to Building Energy Analysis (Welle and See, 2013) outlines the key information applicable to building energy analysis, and is used as the basis for this identification. The stages to which information are applied are based on the RIBA (2013) Plan of Works and split between early stage conceptual analyses, detailed design and system sizing and compliance checking, representing the key stages of BEM development.

In the typical design process of a high performance non-domestic building, where conceptual designs are evaluated and progressed through to technical design of its configured components, its eventual performance is based primarily on compliance with local regulation, fulfilment of client requirements and response to uncontrollable external factors (such as climate and location).

The information relevant to these criteria, and the optimisation of the building's form, systems and operation changes based on the extent to which BEM takes place. For example, a small office building would require less careful evaluation than a large art gallery where internal climate is subject to more careful control. Defining a generic information development process aims to outline necessary information without being prescriptive and making this inapplicable to a large range of potential building developments.

Table B.2 shows that the basic definitions of information types necessary to perform an energy performance simulation are limited; however, the details within these categories are extensive (Clarke, 2001). Each category is also recorded in a BIM environment with very little work required to identify where this information could be stored. For example, Autodesk Revit provides an extensible environment where fields for usage, occupancy levels, lighting and equipment data can be used (Tammik, 2011). Constructions defining walls and windows also provide the user the ability to store thermophysical characteristics (although this information is lost upon export (Costa et al., 2013), Fig. B.2).

Table B.2: Basic information typologies supporting BEM and simulation

Relevant Data	Description
Location	The climate in which the building is located
Spatial Geometry	The form of the building (including orientation)
Space definitions	Layout of the usable spaces within the building
Materials properties	Properties describing thermal performance of fabric (including doors, windows, floors, ceiling, roofs and walls)
Space utilisation	Function of space (describing the likely internal occupant, lighting and equipment gains with operating schedules)
Servicing characteristics	Operating methodology (heating, cooling and ventilation systems)

B.3.2 Information exchange requirements

The information development and handover process was defined, specifically for data pertaining to the performance of the building and the involvement of design stakeholders in this process. The requirements of these stakeholders influences the progression of design, where some information is required prior to the specification of certain elements. For example, prior to the creation of a baseline energy performance model around which plant sizing takes place, there must first be a definitive model describing geometry, location and proposed function of the building. The involvement of stakeholders are identified in Fig. B.3, with the information provided and demanded by each to assist identification of the basic information to be stored and shared via BIM.

B.3.3 Framework development and application

Following definition of the current BEM and design process, these actions are mapped to existing frameworks for quantification of information at key stages during design. The Level of Development definitions provided by the The American Institute of Architects (2012) and Data Drop concept adopted by the BIM Task Group (2012) provide the basis for defining information extent and maturity throughout design, to which BEM relevant information is applied. This is then used to map generation of this data to the BIM design process and provide a means with which to specify at key stages of development the type, and extent of information necessary for storage in the BIM, for use in BEM.

B.3.4 Evaluation

The method of sharing information between BIM and BEM environments and their stakeholders is specified, and this process is applied to the development of a detailed design of two multi-purpose university teaching facilities and a mixed-use residential scheme. The means through which information in these projects is created, stored, shared and utilised is followed, noting key issues encountered, and potential improvements to procedures. The issues encountered are characterised as system-based, skill-based and process-based, and are discussed to contribute knowledge of factors limiting the integration of BIM and BEM in industry adoption of BIM.

B.4 Development and application of a BIM supported BEM procedure

To assess the barriers encountered in attempting to embed BEM information in a BIM environment, key issues (categorized as [Skill], [System] or [Process]) are linked to points for discussion in the Discussion section of this paper.

B.4.1 Information exchange between design stakeholders

Little work has been done to investigate the building energy performance information flow during building design, though several documents provide guidance to integrate low-energy design techniques such as parametric modelling into the process. As part of BuildingSMART's Information Delivery Manual for Building Energy Analysis (Welle and See, 2013) the method of providing BEM support to design is outlined, indicating several of the processes undertaken therein. This procedure changes for each stage of design, as does modelling purpose, but provides a clear method for the creation of validated, accurate building performance simulations. The American Institute of Architects and The Associated General Contractors of America (2013) best practise guide describing the types of modelling inputs and elements altered during design, as well as identifying key stakeholders involved in the process are incorporated in Fig. B.3.

Using existing design progression frameworks, including the activities currently being undertaken in the building design processes evaluated here, Fig. B.3 shows the stakeholders supplying, using and extracting information from the BEM process. The classification of these roles in terms of supply and demand is a simplification not fully representative of these stakeholders in a building's development, but are reasonable in outlining the process. These roles are adapted from Bakens et al. (2005), linked to the information each stakeholder supplies and demands at each stage of development.
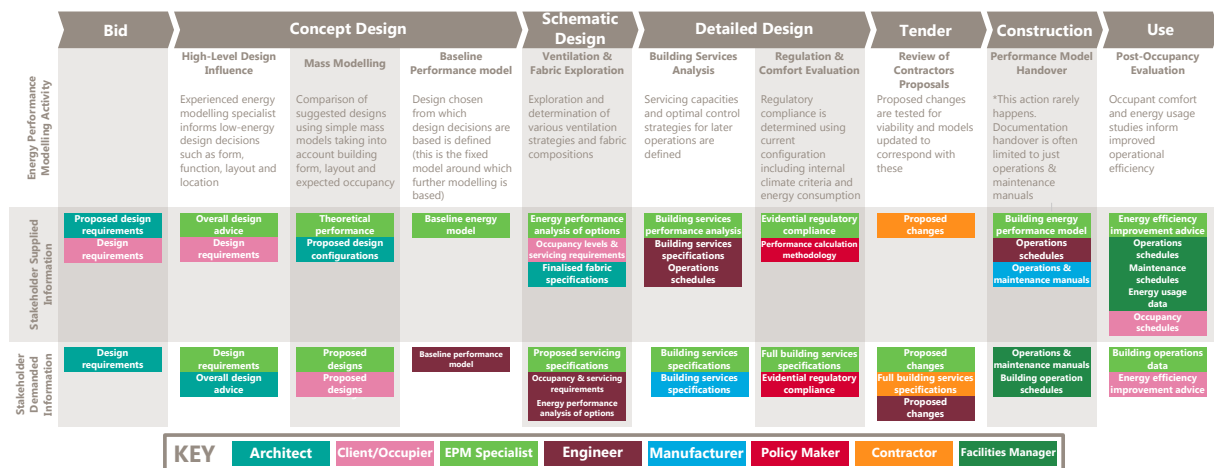
Figure B.3: EPM stakeholder information exchange and development process

Energy modelling can occur at any time during a building's life-cycle. Incremental models contain varying amounts of information, with data generated by prior models used to inform decisions made at the subsequent stages. However, use of this information post-construction is uncommon (Way et al., 2009), due to the complexity of modelling a building

to the necessary level of detail without significant building performance improvement (Prívara et al., 2012), and the costs attributed to this. The impact the building modeller has on design decisions decreases as the design develops (Eßig, 2010) meaning the greater amount of accurate information known early on, the more opportunity there is to make improvements to the design. Early stages are also where most performance related information is generated (Tribelsky and Sacks, 2010). Tupper and Fluhrer (2010) suggest the energy model should inform design; however, this often doesn't happen due to financial and time constraints [system, process].

As demonstrated by He et al. (2014), in each stage of design development, key information regarding the performance of the building is generated and utilised for design progression. Progression can stop if information pertaining to a certain aspect of the design is unavailable (Aouad et al., 1998). For example, regulatory compliance is necessary before the project can be put to tender, or the tendered project is one which fails to comply with regulation requirements.

B.4.2   Information development

Quantizing the building design stages and points of information handover has been applied to BIM through the "data drop" concept suggested by RIBA (2012) and the BIM Task Group (2012). Data drops indicate fixed stages where information should reach a particular level of completion, for verification and use in the next stage of development. Within a data drop, each portion of information describing some part of a model is referenced using an agreed method of classification. For example, BS 1192 (2007) specifies meta-data such as project, location, role, classification and revision. These naming conventions are kept throughout design development [process], allowing those with an understanding of this concept a means of finding the relevant information [skill]. While classification of information is useful for reference, its amount and maturity is essential to indicate model development.

Measuring the extent of information at key stages can be achieved through use of the Level of Development (Level of Development (LOD)) concept. Detailed descriptions of this are given by the The American Institute of Architects and The Associated General Contractors of America (2013), where an arbitrary scale from 100 to 500 is used to indicate the amount of information subject to further change applied to modelled building objects. Within this scale, 350 is also included, as it represents a stage in the project where clash detection takes place – in particular how systems interact with each other.

This schema for defining the information to be collected at different stages does not explicitly include information applicable to BEM (except for basic geometries, external window characteristics and plumbing, ventilation and electrical systems). Information required for simple energy analysis must often be derived rather than collected directly from the original model/format [system]. The minimum required information for BEM is applied to the LOD specification for input into a BIM integrated BEM data repository (Table B.3). As this develops throughout design, information becomes less likely to change and is therefore more representative of the completed building.

These levels of development applied to the current BEM process map indicate the information extent at each of these points of design development, defining the information required to be stored within the BIM to enable effective extraction of BEM information at

Table B.3: Level of Development for BEM parameters during building design

Design stage	Level of development	Key Parameters
Early concept design	LOD100 – Elements represented in model symbolically (no geometric information)	Location (climate, surroundings) Basic thermal zones Generic fabric type Generic thermal profile (occupancy, lighting, equipment) Generic conditions (temperature)
Late concept design	LOD200 – Elements in model represented graphically as generic system with geometries indicated	Spatial geometry (subject to change) Fabric composition Occupancy, lighting and equipment levels Method of servicing (heating/cooling/ventilation)
Early detailed design	LOD300 – Elements represent specific systems with defined location with parametric information included	Fixed spatial geometry Detailed fabric composition (thermophysical characteristics, thermal bridging, infiltration rates) Detailed internal gains schedules Servicing schedules
Late detailed design	LOD350 – Element interfaces with other systems included	Local servicing optimisation Change in use provision Whole building system optimisation
Construction	LOD400 – Fabrication and operation information stored within/alongside element	As-built specifications (geometry, fabric, equipment) Operation and maintenance methods
In-use	LOD500 – All information regarding installed elements is included ready for use by Facilities Manager	External environment records Operations and maintenance records

each stage [process].

B.4.3   Information exchange

The sharing of information between BIM and BEM tools can be problematic, especially when consideration is not made at an early stage in the design process. Without procedures in place for the standard to which a building is modelled, extraction of elements from one environment for use in another can cause errors in data recreation [process] (Welle et al., 2011), gaps in knowledge where data stored in one format is not available in another [system] (Costa et al., 2013) or inability to access information due to proprietary formats [system] (Sanguinetti et al., 2012). Several of these were experienced in the university teaching facilities projects due to the platforms on which information was initially created not matching those with which that information was then developed.

To avoid these issues and evaluate BIM's potential for information capture, storage, utilisation and sharing, a conventional means of data exchange is used to eliminate the potential for these issues to affect the testing of the framework created. Conventional information exchange has long used project extranets and document management systems to collate all relevant design information (Yeomans et al., 2005). It is foreseeable that these will integrate with BIM to collate all relevant design documentation for eventual handover to the building's occupant/operator; however, until then user input is required to share such information.

The procedure followed to create, record and extract information within the BIM and then access this is outlined in Fig. B.4 (demonstrative of a common process followed to create and share information during design, without use of exchange formats). For each of the projects to which the eventual information development framework was applied, the means of exchange between modelling platforms here was a Room Data Sheet (RDS); a spreadsheet containing characteristics exported from the BIM to be referenced in the creation of a standalone energy performance model. Output from simulations are then transferred to the RDS using an export and Dynamo (Autodesk, 2015) import for reinstating this information in the BIM, for use downstream. Until full interoperability is feasible, exchange methods such as this are the go-to means of information transfer in buildings engineering for the exchange of information between multiple modelling platforms.
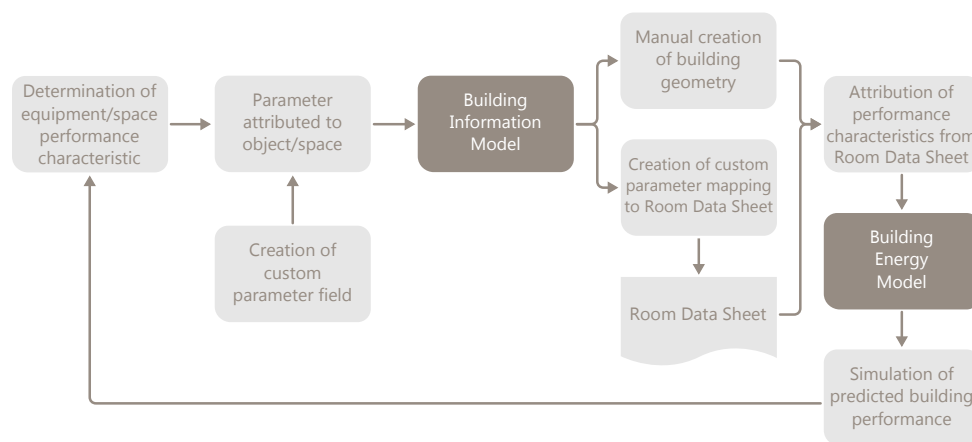
Figure B.4: BIM/BEM information exchange process without open exchange formats

B.4.4   Framework creation

As design progresses, the amount of information available to inform the next stage of design or operations increases. BIM enables the monitoring and management of this information to allow its collection in a CDE.

The information stored within an BEM is dependent on the type of simulation that tool provides. Methods of determining performance range from simple steady state heat transfer, to dynamic finite difference methods. The more complex the model, the more information required to represent the building being simulated. Transfers between BIM software and BEM tools have often focussed on a single aspect of performance modelling, such as HVAC systems (O'Sullivan and Keane, 2005) or envelope geometry (Verstraeten et al., 2008), with a comprehensive transfer of the sum total of performance impacting information is yet to be realised [system]. Direct exchange of data between BIM and BEM design tools remains unattainable (Sanguinetti et al., 2012; Hitchcock and Wong, 2011) [system].

It is therefore justifiable to identify the high-level parameters required for BEM that could be stored in a BIM for use at a later date, but indicating the scope for information storage and reuse in this area. These parameters are outlined in Table B.3 and represent the range of data to be input into the BIM at each LOD before the next stage in design
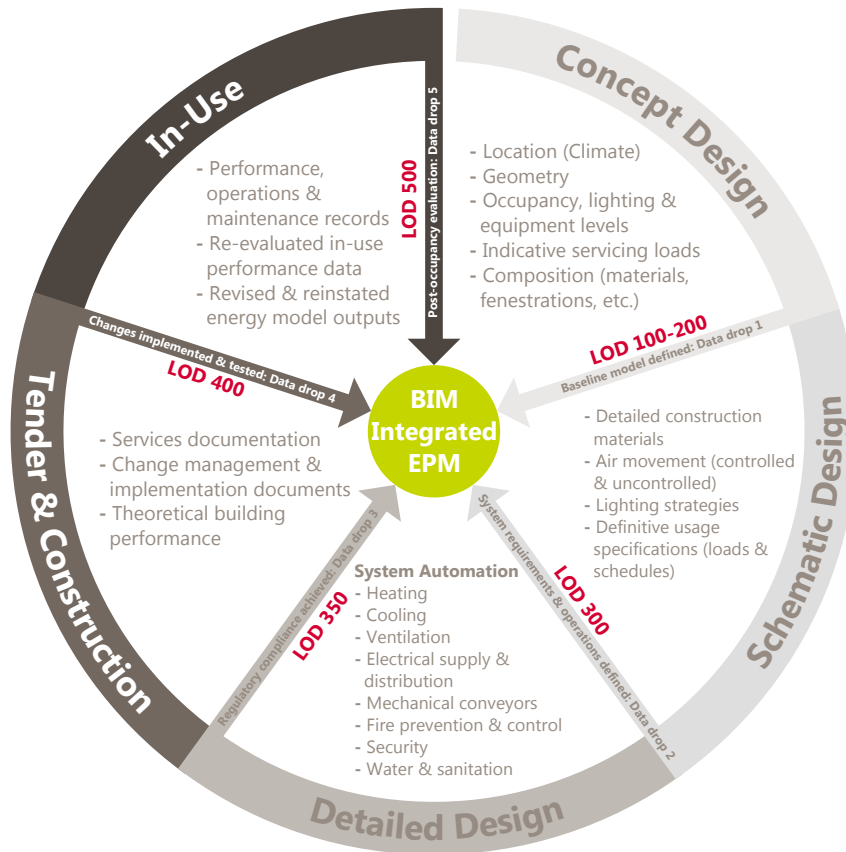
Figure B.5: High-level process map showing decision gates and stages for information extents assessment

can occur; resulting in a comprehensive model describing a building's predicted energy performance assembled throughout the design process.

Mapping these information requirements at each developmental stage, a framework for modelling BEM in BIM has been created, linking the LOD to points at which design progress encounters a major exchange between stakeholders. Fig. B.5 denotes this process, which will be tested in the development of a real project designing a university lecture space and laboratory building.

B.4.5 Application to real projects

The projects in which the exchange of information between BIM and BEM along the defined framework is applied are a university lecture space and laboratory building, a multi-function university teaching space and a mixed-use residential apartment block (all of which reside in the North of the UK). All buildings had their own unique performance criteria to be targeted; however, the methodology used as described here to apportion the relevant information at each distinct stage of development remained the same. Each project was at the early concept design stage upon application of the framework in Fig. B.5, where project documentation was at LOD 200. At this stage, preliminary designs had been completed, determining aspects such as required space characteristics, building geometry and the creation of a baseline performance model. The buildings conditioning systems were yet to be defined; however, indicative conditions were specified. Each project

had different development teams and external designers, meaning the specification for model development was different throughout. Within this, the method used to exchange information between BEM and BIM was adjusted to adhere to the requirements of that particular project [system, process].

The BIM models developed for each project used generic objects to represent equipment, populated with key performance characteristics to be represented in the BEM. The model built originally by the architects and later used by other disciplines (mechanical engineers for systems coordination) was used as the basis upon which data was attributed. This enabled basic templates to be used that were pre-set with existing components describing performance that could be adjusted by the building physicist for individual building characteristics. At the schematic design stage, information developed by the mechanical engineers was input into RDSs (as defined in LOD 300, Table B.3) and automatically included in the BIM using a Dynamo script reading these sheets and updating fixed parameters within the BIM environment with updated values. In some cases, information was not suitable for attribution using this method, relying instead on reference to locations in the project filing system [skill] separate to the BIM reference model for use by the energy modellers, without a direct method of accessing this data.

One such example of this information is time-series data comprising half-hourly space performance characteristics used to size equipment for detailed design. At most, current BIM tools provide fields for single value descriptors without consideration of change over time (Gerrish et al., 2015) [system]. A value range was used in place of the full record of values in the BIM, with reference to external datasets containing all data for investigation by the BEM specialist.

LOD 300 establishes the intended thermal characteristics of the building, including its materials specifications and construction quality. These characteristics are stored as object meta-data attached to materials in the BIM. As previous attempts of exchanging data between the BIM and BEM using open exchange formats had failed (Fig. B.1), on the university teaching facilities project the performance characteristics were extracted to the RDS for manual recreation in the BEM [skill, process]. At this point, regulatory compliance is assessed prior to reaching Data Drop 3 (Fig. B.5). Compliance checking of building performance is currently available in BIM tools, but these do not fully address all aspects required to definitively state whether a building will achieve a specific standard (Greenwood et al., 2010) [system].

The HVAC schematic at the detailed design stage is created by engineers based on the requirements of the building defined by the BEM (and obtained via the RDS link with the BIM environment). From these, a schematic of services is created outside BIM (due to issues modelling such detail, and the familiarity of those designers with BIM as a mechanical services modelling tool) [skill]. Modelling stops after checking these servicing layouts for their provision of conditioning capacity; however, this was completed separate from the BIM with data from the RDS informing system interoperation.

Use of BIM as storage for the sum total information describing each projects provided a benefit in the following stages of design development, as an export of all relevant information at each major handover was made available through a simple Dynamo-based export of project information from the BIM, containing all information required at these stages. This was then used during later development and where requests for information came in when a version of the BIM authoring tool may have changed and access to that

information was then made more difficult [process]. Following Data Drop 3 (LOD 350), simulated performance data is used to minimise energy consumption during use. At this stage, operational strategies are finalised for input into the Operations and Maintenance (O&M) manuals [process] ready for handover to building operators. A potential benefit of keeping descriptive information in a format other than the BIM native format is data accessibility to those without the necessary BIM tools [system], nor the possibility of data being lost through export to an incomplete exchange format [process].

B.5   Discussion

The application of the framework for information storage, sharing and access was intended to test whether BIM could be used to improve information accessibility for BEM. The process of determining a building's theoretical performance using pre-construction information was defined and modified to include its generation within a BIM environment. In the following discussion, the issues encountered during application of this framework, and challenges to be overcome in reaching a more integrated BIM and BEM design process are presented.

B.5.1   Systems-based issues

Disintegrated information

Information storage capabilities of BIM tools currently restrict the inclusion of large time-series performance datasets produced by BEM simulations. While summary of this data in a BIM environment is possible, information is derived from simplifications rather than the original data resulting in silos of unlinked information.

Until a whole building-modelling suite including all aspects of performance evaluation exists, methods of sharing information between parallel but non-integrated development platforms will continue to be developed (Kim et al., 2012; Hitchcock and Wong, 2011; Bazjanac, 2008; O'Sullivan and Keane, 2005) prior to open interoperability and widespread adoption by modelling software providers. Changes in processes used and skills held by those using the systems is required to facilitate both the development and adoption of these tools.

Information exchange

In linking data between BIM and non-BIM systems, systemic challenges exist in enabling data exchange through suitable formats. Prior to process change, identification of what information should be available must be addressed (for example, the key performance descriptors of a piece of mechanical equipment). Attribution of parameters to objects in a BIM enable information to be stored adjacent to a representation of that object and its constituent system. Within the IFC and gbXML schemas there is potential for such information to be stored and exported between modelling platforms; however, this information is not made available by the tools exporting to the open exchange formats. For example, BEM tools typically only manage a single aspect of performance extracted

from a BIM environment. Eastman et al. (2011, p. 168) suggest a suite of tools will emerge where information in a BIM can be checked and prepared for extraction into analysis tools without the lengthy and complicated process of manually extracting, checking and re-inputting information for simulation.

Information access

Post-construction, the information generated during design must be accessible to provide a rich source of operations and maintenance data, assisting the building operators in the ongoing management of the building. If all information is to be stored in a BIM environment, then some means of extracting it upon design completion is necessary. Use of BIM authoring tools to do so is costly for building operators who would need to purchase software and invest in training to extract relevant information. Instead, this information is handed over upon completion in some agreed upon format, for input into another system or as simple indexed folders of documents, spreadsheets and drawings, limiting the opportunity for data to be used later in the building's life-cycle.

B.5.2   Skills-based issues

Modelling to suit multiple purposes

Creation of a model suitable for the attribution of parametric object data is essential to support use of that model across disciplines, without risk of data loss through incorrect interpretation of the embedded information. Noted during this framework application was the need to partially remodel the supplied architectural models to suit attribution of building services layouts, structural elements and storage of space related performance data. Commonly, the quality of the supplied model was insufficient to support automation of some design aspects, most likely a result of human error in the original modelling process (Safin et al., 2008) (such as inaccurate space bounding), and most of these were present as a result of human error.

Querying a CDE

Information stored in a model is used by those accessing that model at a later stage who must have the necessary skills to access this information. Due to the distinct differences between the fields of BIM and BEM (often with different teams working separately from each other), the skills required to model in BIM authoring tools such as Revit or ArchiCAD are significantly different to the skills required for modelling in BEM tools such as EnergyPlus or IES-VE. The BEM specialist must know where to look within the BIM for the information they need, requiring them to be familiar with BIM tools and the location of the data pertinent to their utilisation (Gu et al., 2009).

In the example project, all BEM stakeholders had issues in familiarising themselves with the BIM authoring tools for extraction of relevant embedded data (such as zoned air supply, location and distribution of services and equipment networks and material thermophysical properties); however through use of the more familiar spreadsheet-based RDS these issues were overcome.

B.5.3 Process-based issues

Use of incorrect information

Linking the BEM development process to data drops (BIM Task Group, 2012) enabled the amount of information required at these stages to be defined. Through including BEM criteria such as equipment performance requirements within these data-drops, this information was more likely to be used and kept up-to-date during design development, reducing the potential for use of inaccurate information. The LOD concept seems to include definitive information more relevant to design progression and performance improvement. While building users are beginning to demand asset registers (Love et al., 2014), it is also beneficial to know about the systems in place and how best to use them to improve energy performance. Through utilising the full parametric information storage capabilities of BIM software, a data trail can be followed to indicate where problems occur in design development (Nassar, 2010), and the decisions made during this process to result in the specification of the system being evaluated. This could allow more effective fault rectification, and feed back into later designs to avoid future issues.

Duplication of effort

Segregation of modelling using different tools and information standards requires some form of open exchange format; however, some tools do not support export of relevant data, nor accurate interpretation of data. As such, information may be duplicated which adds further intricacy to the already complex process, potentially confusing what information has been generated already, whether the most up to date version of information is being used to further overall design, and increasing unnecessary rework (Anumba et al., 2008).

Information accuracy and reference

The term "single source of truth" has been used in reference to BIM, mainly in terms of its use in design (as exemplified in this research); however, there may be benefits in the resolution of disputes and information requests later in the design and building lifetime. A snapshot of a design stage is possible given the capacities of BIM tools to store various versions of the same model at different points in time. Checking the indicative performance against actual performance may become more widespread with the impending implementation of performance based contracts (DECC, 2015).

B.6 Conclusions

In this study we presented an process map for exchanging information between building designers and BEM practitioners highlighting the extents of information required at key stages throughout the construction design process. The process of design of a building's energy performance, and its design using BIM as the method of information storage throughout was followed, identifying the current barriers to integration of these two modelling platforms.

The range of sources available for implementing process planning and information monitoring systems in building design development offer comprehensive instruction in how to manage the building information throughout design and use. Examples include the RIBA (2013) Plan of Works and PAS 1192 (BSI, 2013), but none outline the management of energy performance information, which changes as a building's design progresses. The framework outlined here evaluated how information pertaining to the evolution of a building's energy performance design is stored, exchanged and accessed to ascertain the issues currently preventing effective use of BIM as a means to achieve coordination across disciplines in this process.

The specific data stored within a BIM environment required by BEM for the purposes of informing building design at particular stages of that design progression has been defined with the following recommendations made for future efforts moving towards an integrated cross-discipline design environment:

– Open exchange formats are not currently viable for a large proportion of information exchange purposes. As a result, proprietary formats are specified for exchange in real projects to avoid potential errors;

– Use of conventional methods of data transfer (spreadsheets) remain due to user familiarity with these processes. Training is required by all those utilising information stored within a BIM environment, if only to provide knowledge of how information is accessed to support their activities downstream;

– Up-to-date information describing a building design creates a more accurate representation of that building. This information can be stored in a BIM environment, but responsibility for the update of this information is essential to ensure it is accurate and usable;

– BIM Execution Plans fail to account for those working outside the current BIM environment. Information generated here is not commonly specified for inclusion in the BIM, and until it is the model remains a mere 3D representation of 2D geometry with no meta-data usable in later versions of that model; and

– Processes used to access and update information in a CDE should be supported by both the tools being used to achieve this, and user skill in interacting with these tools. Without both, using BIM to support any "non-BIM" design tool will not be feasible.

Industry practitioners managing the design development of building require an understanding of how that design progresses, and the means of sharing information in an efficient and accurate manner. Use of a framework such as that suggested here could assist designers to include information in their models that can then be used to understand a building's operational performance, and provide a definitive source of information that can be referenced by all members of the design team.

Future research in the attribution of in-use building performance data into the CDE for the management of a building's performance in both design and use can use these findings to focus work in the areas requiring most development.

Acknowledgements

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C   Paper 3

Gerrish, T., Ruikar, K., Cook, M. J., Johnson, M., and Phillip, M. (2015). *Attributing in-use building performance data to an as-built building information model for life-cycle building performance management.* In: Proceedings of CIB W78. 27th-29th October 2015 Eindhoven, The Netherlands: CIB.

Attributing in-use building performance data to an as-built building information model for life-cycle building performance management

T. Gerrish, K. Ruikar, M. Cook, M. Johnson, M. Phillip

The construction industry is moving towards an holistic design environment facilitated by Building Information Modelling (BIM), where information generated during design can be used as the basis for operational management of the built asset. However, this information is often left unchanged post-construction. The data generated describing building performance, such as energy consumption, spatial temperatures and equipment performance cannot currently be managed in a BIM environment. Making use of existing data storage mechanisms and tools would enable better management of a building's energy performance, but existing data management systems fail to provide a framework to do so.

This paper forms part of a research project looking at how BIM can be used as a life-cycle building performance management tool, identifying the necessary steps move from towards integration of performance data in the holistic model.

C.1 Introduction

Building Information Modelling (BIM) is being applied to more aspects of building design, with research in this area detailing novel uses of information modelled in this manner throughout most fields in the Architecture, Engineering and Construction (AEC) industry (Becerik-Gerber and Kensek, 2010). The construction industry has yet to fully adopt BIM as its default process for information generation, storage and retrieval during building design. Technical limitations of modelling tools force designers (e.g. architects, engineers, physicists) to resort to conventional systems of design development and documentation such as room data sheets and 2D CAD.

Within industry literature BIM is commonly advocated as advantageous in designing sustainable buildings (Azhar et al., 2011; Motawa and Carter, 2013). The benefits experienced from application of BIM tools and technologies are hampered by lack of interoperability between various modelling platforms (Ferrari et al., 2010), in particular the transition of information between the common design model and specialised building energy performance analysis tools (Moon et al., 2011). One such prevalent issue is the manual data re-entry between applications identified by McGraw Hill Construction (2007) to be the primary cause of time lost through non-interoperability, and while methods for overcoming such problems are developed in an ad-hoc basis, this continues to be a problem throughout the construction industry.

Use of data describing a building's spaces and the equipment conditioning it is one area where the use of BIM to contain descriptive data and manage large amounts of data could support ongoing commissioning and management of a building's in-use performance. Exploration of the attribution of data to objects (digital representations of building elements describing spaces and equipment) within the building model, and the potential

for measured in-use performance data those objects is made, using the industry standard open format Industry Foundation Class (IFC).

C.2   Background

Utilisation of building energy performance information is widespread during design, whilst in-use performance data supports continuous commissioning activities in a narrower field. Both areas are developing rapidly through implementation of BIM tools, processes and technologies, but building performance management remains a distinctly separate field due to its lack of interoperability with these.

C.2.1   Lifecycle BIM and building energy performance management

During Design

Interaction between the modelling of a building's energy performance and that of its spatial layout, conditioning systems and operations in BIM has been explored in depth (Aksamija et al., 2011; Azhar et al., 2009; Bazjanac, 2008; Corry et al., 2011; Schlueter and Thesseling, 2009; Welle et al., 2011); however, these focus predominantly on the management of design information and ability to transfer this information between the two very different modelling environments.

O'Donnell et al. (2013) developed a method to transform Architectural BIM to an energy analysis tool via its IFC export, encountering issues such as incomplete models, inaccurate modelling techniques and over detailing each contributing to the inability to simulate directly from the BIM. These issues are mostly overcome through careful modelling; however, in the management of energy performance impacting information changing over time, models have few capabilities to store this data for interpretation.

During use

Post-construction, the ongoing performance of an operating building can also be simulated to evaluate its performance in comparison with how it was originally predicted, or to better understand issues arising in that building. Many construction projects use this to improve designs in later projects (Torcellini et al., 2004), but most benefit can be achieved through better operation of the existing building stock. Industry trends show adoption of continuous commissioning for better building control (Hampton et al., 2006) and in-use assessment (BRE, 2013), using these tools and techniques in conjunction with initiative such as Soft Landings (BSRIA and Usable Buildings Trust, 2008).

BIM tools and capabilities can be used to enhance the building operations process, where possible integrating the BIM and energy modelling processes into a parallel environment. Here, continuous assessment of building performance can be made based on the live conditions within that building for indication of potential faults and issues during use. Attribution of measured performance data to objects within the BIM has been made by Wetter (2010) using the Building Control Virtual Test Bed. This platform enables the

co-simulation of actual and predicted performances, utilising the BIM of the simulated building as its basis (O'Neill et al., 2014; Pang et al., 2012). Embedding BIM into this process brings more issues into an already complex multi-program simulation and analysis system, with Bailey et al. (2011) encountering issues with limited data access, lack of interoperability between platforms and the need for data visualisation to get meaning form the vast amount of measured data.

C.2.2 Data fragmentation

BIM is currently being implemented to manage information developed during the design of a building; however, not all information developed is attributed to this model and instead remains in supplementary documents produced throughout the course of working between multiple organisations (Dossick and Neff, 2010). Love et al. (2011) suggested BIM as a medium to assist reduction of errors inevitably created during this fragmented approach; however, as with previous methods of design development, the need for error checking throughout its generation is required perhaps more-so, given the rapid changes made to several areas of the building's design using BIM.

Transfer of information between modelling platforms for different purposes is notoriously difficult (Verstraeten et al., 2008; Welle et al., 2011), often resulting in the creation of an entirely new model for a singular purposes (modelling to the standards required by this purpose), duplicating work and reducing time available for application of its results). Reducing work duplication could be enabled through populating and sharing information in a singular environment, requiring development of a common development platform suitable for attribution of information from the numerous fields of AEC design. The potential for this platform has been explored by Jiao et al. (2013); however, current modelling tools or storage formats are not suited to management using the single model environment. More specifically, IFC (the closest we are to a modelling format working between current software tools) has been identified as one "*not well adapted [to] the management and the evolution of data*" (Vanlande et al., 2008).

C.2.3 Simulated and measured building performance metrics

The information generated by Building Management System (BMS) and building energy simulation systems can be compared in several ways. Direct comparison however, may not be suitable in some aspects of this data due to the method in which it is reported, or what it actually describes. For example, in a thermal model the space temperature reported is for a uniform distribution throughout the zone. Within the building, the comparable temperature reading is only valid for the point at which that temperature is recorded (see Fig. C.1).

Modelled plant equipment can also be difficult to directly compare to monitored equipment, where the BMS records system flow and return temperatures while simulations are limited to whole system performance characteristics and their effects on the modelled environment. Comparison of the output metrics from an energy performance simulation and a BMS shows parameters due the different purposes for these areas of performance measurement cannot in some cases be directly compared. For example, sensed space temperature is comparable to predicted space temperature, whereas sensed equipment
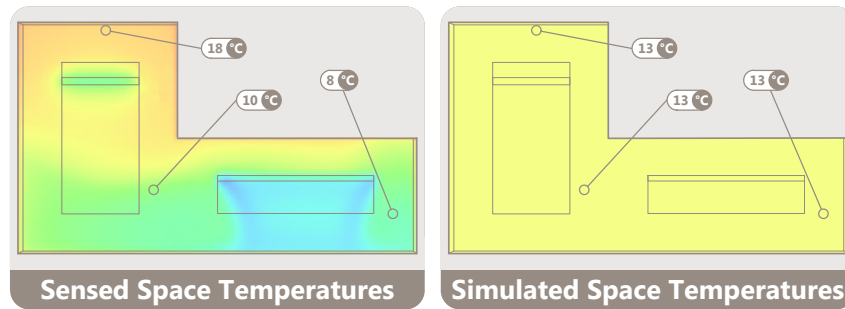
Figure C.1: Sensor location and representation of space performance

flow/return temperatures may not be directly compared to predicted equipment energy consumption). The vast number of variables that can be output by an energy performance simulation program mean a comprehensive list is outside the scope of this work; however, those variables being measured by an example BMS can be used to show what may be linked and used to compare predicted and operational performance. Fig. C.2 shows the potential comparability between these variables and where sensed data differs from simulation data.

Figure C.2: Data generation during prediction and operation of a building

Measured and predicted variable comparability

In most cases the direct comparison of measured and predicted datasets is not possible, where predictions from simulation are used either for plant sizing or environmental compliance (Maile et al., 2007). The primary difference between predicted and monitored data are the types of variables being output. Simulations output holistic building energy performance metrics such as space temperatures and overall equipment loads, whereas monitored data can measure specific pieces of equipment contributing to those values. These monitored variables represent the resultant conditions from numerous contributing factors whereas during simulation these contributing factors can be investigated directly.

Indirectly comparable variables may be manipulated into a comparable form (for example simulated Cooling Plant Load being compared to the total energy consumed

by Cooling Equipment); however, given the complexity of the systems in place and the number of modes of operation this becomes infeasible

This suggests the comparison of in-use performance metrics (resultant space temperatures, humidity, CO_2 concentration) rather than comparison of individual plant equipment conditioning those spaces would be more achievable. Several issues must be overcome for this to work, not least of all ensuring the accuracy of the simulation to the in-use building. A simulated output might closely represent actual conditions of the inhabited spaces, but for entirely wrong reasons. In many attempts to simulate building performance impacted by its embedded plant equipment challenges have been encountered in accurately representing the bespoke in-place systems (Zhou et al., 2013). The model developed for the building studied here found similar issues, with lack of simulation capabilities of non-standard equipment, the effects of which were accounted for through alteration of equipment performance – further disassociating simulated from actual performance.

HVAC equipment-specific predictive modelling issues

Types of Heating, Ventilation and Air-Conditioning (HVAC) performance modelling have been defined by Trcka and Hensen (2011). Distinguishing between the aspects of a building contributing to its energy performance, they defined three areas: Main/Primary Plant, Local/Secondary Plant and Controls (Fig. C.3). These components can be modelled, however the purpose of this modelling was split between modelling for the purposes of component response simulation (amount of conditioning within a space), and the evaluation of environmental performance characteristics (space temperature, pollutant concentrations, humidity etc.).

The component portion of this HVAC analysis is where BIM could potentially become forefront in the compilation and continued development of whole building models, utilising its capacity for object data attribution to supply up-to-date information to the analysis models used to predict building performance. Later use of this model to assess ongoing operations of the building could then integrate the control of the installed systems fed from these components to monitor, record and improve upon current whole building servicing performance.
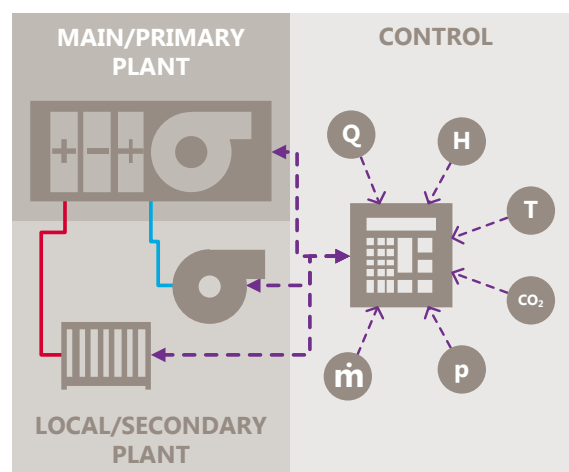
Figure C.3: HVAC plant make-up for simulation

Measured data and simulated data format

In a typical BMS, monitored environmental and equipment performance data is stored in a Structured Query Language (SQL) server, holding historical performance data for the past years variables of main plant flow/return values for all HVAC equipment, local equipment performance characteristics such as zone temperature (controlling CHW flow rate), zone CO_2 concentration (controlling zone air supply) and valve positions describing the operation of these key pieces of servicing equipment. In comparison, as shown in Fig. C.2 the data recorded within a simulation gives more indication of whole building characteristics and environmental conditions.

The format in which the BMS data is recorded means further evaluation and analysis requires several steps to access the necessary data. Access to this information varies based on the BMS implemented, but the system used as an example here is representative of the process encountered across several of these (Ulickey et al., 2010). Initially, the sensors in place throughout the building record operational data at pre-defined intervals. This is then stored within the SQL database and accessed by the BMS interface for local and historical assessment of conditions. Data extraction relies on the user being able to access this SQL database and defining parameters for extraction between time periods, with the most common format for export being plain text Comma-Separated Values (CSV).

An energy analysis model is less dependent on the system in place to give access to simulated performance data; however, the proprietary nature of many performance simulation tools means access to simulation output without use of the simulation tool is not easily achieved.

C.2.4   Industry Foundation Class format

The IFC schema developed by BuildingSMART (2013) aims to improve the interoperability between modelling platforms. The capabilities of this format for data storage relies on its hierarchical object-based nature (elements in the building are objects with attributed information). The interoperable aspect of the format requires that it forms a lowest common denominator approach, where the information required to describe the building is exported without any proprietary functionality available within the specific tool used to create that file (Fig. C.4).
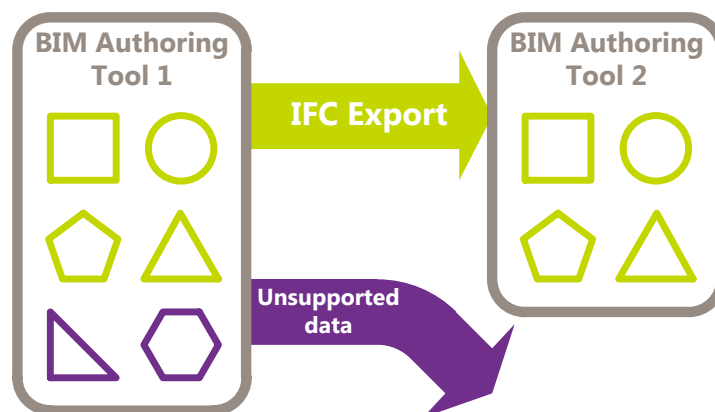
Figure C.4: Data loss experienced through IFC "lowest common denominator" approach

Objects describing HVAC systems require performance data attribution to move past mere geometric representation, which is possible given IFCs extensibility. However, the IFC framework does not currently allow for a wide range of dynamic data (that which changes during the operation of the building it describes), using maximum and minimum values for variables during its use in the design process. These suffice for design purposes where they are used for determining limit states, but when moving into the building's life-cycle where operations, set points and consistently changing operational metrics are prevalent, they become less useful.

C.3   IFC dynamic data storage feasibility

This paper is not a test of the IFC software capabilities, these are well defined and used throughout industry for data storage and translation (Bazjanac and Maile, 2004; Bazjanac, 2008; Kim et al., 2012; Rio et al., 2013; Verstraeten et al., 2008). The focus here is to determine how dynamic building performance data could best be stored within, or in conjunction with IFC data as a platform for supporting building performance management.

Basic time-series performance data (measured values attributed to a particular point in time) requires several principles to be followed in order for this information to be usable for further analysis:

– The data must be accessible for its further use in managing the building's performance;
– Reference to the location and variable each series of data represents must be made at the point of its collection;
– An object must exist to which that data can be attributed (e.g. element, space, building);
– Object meta-data must describe what this data indicates and provide context (e.g. maximum/minimum expected values, dependant variables; and
– Data resolution must be suitable for the metric being monitored (high enough to show change over time while low enough to minimise dataset size).

These rules are followed to ensure accurate representation of a building's energy performance from sensors (assuming these sensors are properly placed and reporting correctly), allowing this data to then be attributed to objects within the IFC.

C.3.1   Recording in-use performance in the IFC schema

The core data schemas around which the definition and description of objects within the model and their attributes are managed, show provisions for the recording of live performance data along a time series (using IfcPerformanceHistory). Attribution of these values to objects or spaces defined within the IFC are not yet realised; however, given IFC's object-oriented language there is potential for historical performance data fed from in-place sensors to populate an ongoing performance model (Bazjanac and Maile, 2004; Bazjanac, 2008; Khan and Hornbæk, 2011). The feasibility of managing time series performance data into an IFC is unexplored, and initial thoughts on this matter suggest that this type of data is not best suited for inclusion within the IFC format given the potential size of datasets and challenges encountered in managing these currently.

C.3.2 Objects in the IFC schema

Key elements of the IFC schema, shown with their hierarchy and relationship in Fig. C.5 are those used to store meta-data attributed to objects, within the entire IFC schema. These regions in the schema are those where descriptive performance data could be attributed, describing equipment performance and environmental performance, linked to the objects monitoring that data (sensors).
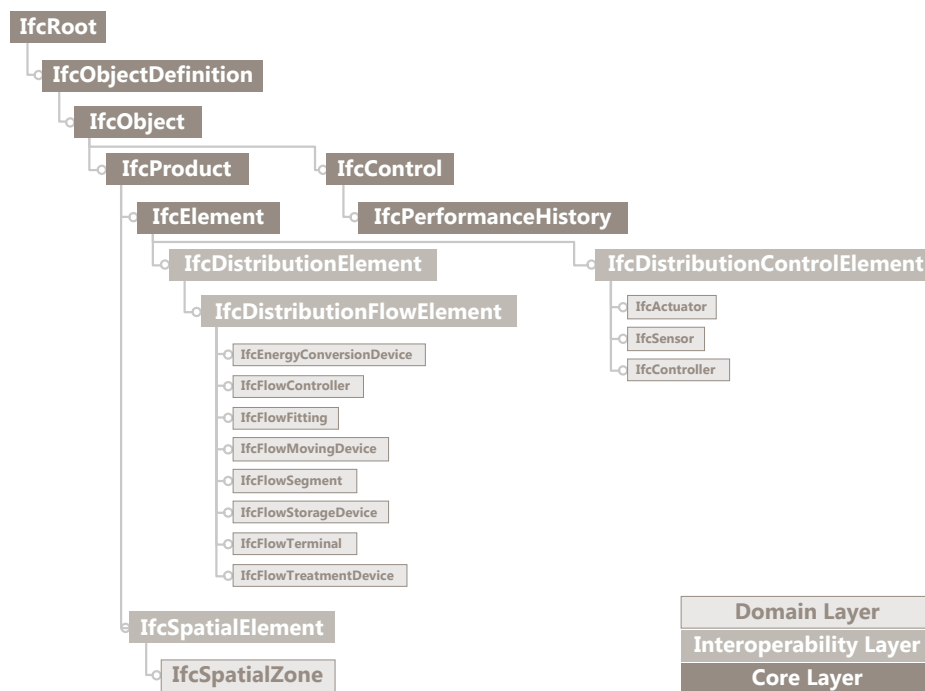
Figure C.5: Data hierarchy for relevant IFC elements

For example, in the IfcSensor object, as with all objects within the IFC, properties shared across all other sensors are defined using PsetSensorTypeCommon. Object specific attributes for a gas sensor are defined within PsetSensorTypeGasSensor, with description of the gas being detected (GasDetected) and area represented by the sensor (CoverageArea) stored as IfcLabel and IfcAreaMeasure respectively.

A static descriptor for the value being sensed (SetPointConcentration) is stored as an IfcPositiveratioMeasure (Fig. C.6). These values ascribed to the object within the IFC are used to define an in place sensor within the completed building as part of that buildings control and performance measurement systems.

In conjunction with object-specific performance attributes, spaces within the IFC also hold some ability for property attribution. IfcSpatialElement contains property sets describing various performance attributes for that space (Fig. C.7). As with those descriptors for the sensor objects, these properties are static values for the performance of that space.

Performance data within the IFC schema

Objects with their static descriptors are commonly used to transfer information between modelling tools during the design process. Modelled components (if translated correctly)

Pset_SensorTypeCommon

Reference (IfcIdentifier)
Status (IfcLabel)

Pset_SensorTypeGasSensor

GasDetected (IfcLabel)
SetPointConcentration (IfcPositiveRatioMeasure)
CoverageArea (IfcAreaMeasure)

IfcSensor

Pset_SensorHistory

Value (IfcTimeSeries/IfcReal)
Direction (IfcTimeSeries/IfcPlaneAngleMeasure)
Quality (IfcTimeSeries/IfcLogical)
Status (IfcTimeSeries/IfcLabel)

Figure C.6: Sensor attributes within the IFC schema

Pset_SpaceFireSafetyRequirements

FireRiskFactor (IfcLabel)
FlammableStorage (IfcBoolean)
FireExit (IfcBoolean)
SprinklerProtection (IfcBoolean)
SprinklerProtectionAutomatic (IfcBoolean)
AirPressurization (IfcBoolean)

Pset_SpaceOccupancyRequirements

OccupancyType (IfcLabel)
OccupancyNumber (IfcCountMeasure)
OccupancyNumberPeak (IfcCountMeasure)
OccupancyTimePerDay (IfcTimeMeasure)
AreaPerOccupant (IfcAreaMeasure)
MinimumHeadroom (IfcLengthMeasure)
IsOutlookDesirable (IfcBoolean)

Pset_SpaceLightingRequirements

ArtificialLighting (IfcBoolean)
Illuminance (IfcIlluminanceMeasure)

Pset_AirSideSystemInformation

Name (IfcLabel)
Description (IfcLabel)
AirSideSystemType (IfcLabel)
AirSideSystemDistributionType (IfcLabel)
TotalAirflow (IfcVolumetricFlowRateMeasure)
EnergyGainTotal (IfcPowerMeasure)
AirFlowSensible (IfcVolumetricFlowRateMeasure)
EnergyGainSensible (IfcPowerMeasure)
EnergyLoss (IfcPowerMeasure)
LightingDiversity (IfcPositiveRatioMeasure)
InfiltrationDiversitySummer (IfcPositiveRatioMeasure)
InfiltrationDiversityWinter (IfcPositiveRatioMeasure)
ApplianceDiversity (IfcPositiveRatioMeasure)
LoadSafetyFactor (IfcPositiveRatioMeasure)
HeatingTemperatureDelta (IfcThermodynamicTemperatureMeasure)
CoolingTemperatureDelta (IfcThermodynamicTemperatureMeasure)
Ventilation (IfcVolumetricFlowRateMeasure)
FanPower (IfcPowerMeasure)

Pset_SpaceThermalRequirements

SpaceTemperature (IfcThermodynamicTemperatureMeasure)
SpaceTemperatureMax (IfcThermodynamicTemperatureMeasure)
SpaceTemperatureMin (IfcThermodynamicTemperatureMeasure)
SpaceTemperatureSummerMax (IfcThermodynamicTemperatureMeasure)
SpaceTemperatureSummerMin (IfcThermodynamicTemperatureMeasure)
SpaceTemperatureWinterMax (IfcThermodynamicTemperatureMeasure)
SpaceTemperatureWinterMin (IfcThermodynamicTemperatureMeasure)
SpaceHumidity (IfcRatioMeasure)
SpaceHumidityMax (IfcRatioMeasure)
SpaceHumidityMin (IfcRatioMeasure)
SpaceHumiditySummer (IfcRatioMeasure)
SpaceHumidityWinter (IfcRatioMeasure)
DiscontinuedHeating (IfcBoolean)
NaturalVentilation (IfcBoolean)
NaturalVentilationRate (IfcCountMeasure)
MechanicalVentilationrate (IfcCountMeasure)
AirConditioning (IfcBoolean)
AirConditioningCentral (IfcBoolean)

IfcSpatialElement

Pset_ThermalLoadDesignCriteria

OccupancyDiversity (IfcPositiveRatioMeasure)
OutsideAirPerPerson (IfcVolumetricFlowRateMeasure)
ReceptacleLoadIntensity (IfcReal)
AppliancePercentLoadToRadiant (IfcPositiveRatioMeasure)
LightingLoadIntensity (IfcReal)
LightingPercentLoadToReturnAir (IfcPositiveRatioMeasure)

Pset_ThermalLoadAggregate

TotalCoolingLoad (IfcPowerMeasure)
TotalHeatingLoad (IfcPowerMeasure)
LightingDiversity (IfcPositiveRatioMeasure)
InfiltrationDiversitySummer (IfcPositiveRatioMeasure)
InfiltrationDiversityWinter (IfcPositiveRatioMeasure)
ApplianceDiversity (IfcPositiveRatioMeasure)
LoadSafetyFactor (IfcPositiveRatioMeasure)
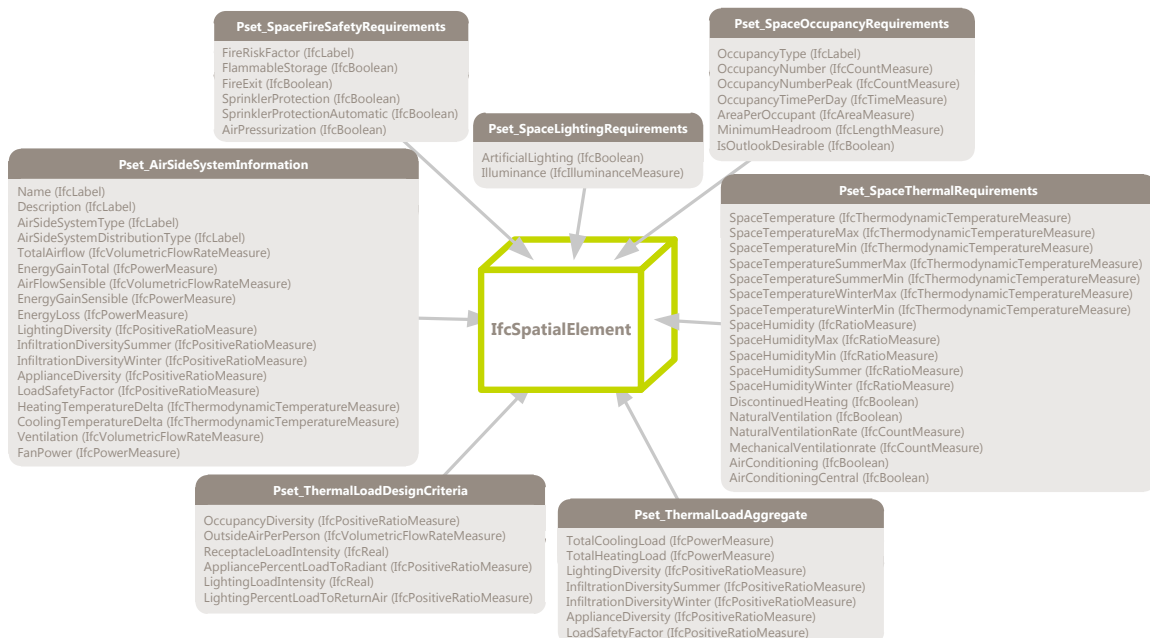
Figure C.7: Spatial performance attributes within the IFC schema

can be viewed and interpreted by software to inform the next stage of building design, and populate datasets such as COBie (Wix, 2008) for object schedules asset management. The information recorded here is assigned by the modelling tool, and remains in that state until further change. For example, within the IfcSpatialElement (Fig. C.7), the variable TotalCoolingLoad within Pset_ThermalLoadAggregate defines the maximum expected cooling load for that space calculated during design. These static descriptors are useful for giving a picture of the building at a single point in time, but not as its operations change throughout the building's lifetime.

Building energy performance information is not static, and each value relates to a specific time at which it was predicted or measured. As such, static descriptors cannot be used to portray a complete image of that buildings current and past performance for use in improving performance and indicating potential faults with its operations. A dynamic variable must then be attributed to these measured variables to link with, or be stored within the IFC scheme attributed to its parent object. In the context of this work and the current IFC schema, dynamic performance data relates to a measured variable at fixed points over time giving a time-series dataset representing a specific aspect of space or object performance.

Several methods of storing time-series data exist within the current IFC schema, described here:

IfcTimeSeriesValue

This entity lists a series of values attributed to points in time. Given that performance tends to be recorded at fixed intervals this may be part of the IfcRegularTimeSeries negating the need to attribute an IfcTimeMeasure to the values recorded. Each measurement is attributed a timestamp (IfcDateTime) to distinguish when it was recorded, with list values stored as an IfcValue (Fig. C.8).
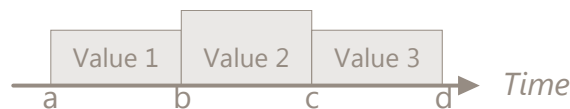
Figure C.8: IfcTimeSeriesValue data collection formatting (BuildingSMART, 2013)

IfcPerformanceHistory

An alternative to recording time series data may be found in the IfcPerformanceHistory as part of the Control Extension to the core IFC data schemas. This entity uses the same method for recording object performance history as IfcTimeServiesValue, using time series values with time stamps. However, it can be linked to the property sets of a particular object to describe an aspect of that product, group, process or resources performance (primarily in the IfcDistributionElement subtypes for building services elements). This entity is used to document actual performance characteristics over time from measured data from building automation systems (BuildingSMART, 2013). An IfcSensor which would be the device measuring this performance history would however, be unable to utilise this function as it is not classed as a group, process, product or resource.

The particular aspects of performance may be grouped into four types, wherein the aspects listed under IfcProduct are those most relevant to building energy performance:

Figure C.9: IfcPerformanceHistory control assignments

Practical storage of time-based performance information in each of these entities is not currently an in-built capability of commonly used BIM authoring tools, nor is consideration of the model as a platform onto which in-use performance metrics could be attributed. Attempts to relate live data to an existing (or developed) model has been made by Attar et al. (2010) and Khan and Hornbæk (2011) where manual correlation between measured spatial performance metrics (pressu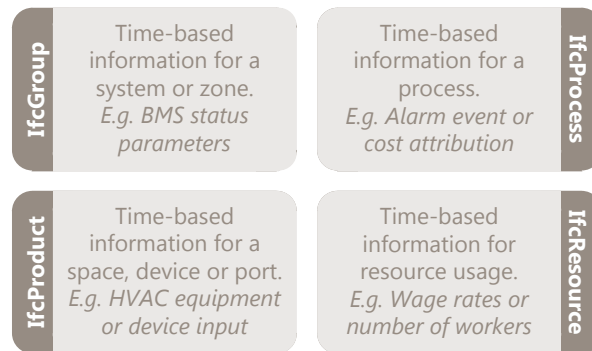re, light, current, noise, CO_2, movement, humidity and temperature) was demonstrated using Revit to represent the building's in-place sensors. These were supported with datasets recorded by the BMS to enhance understanding of performance measurement using a BIM platform. This was achieved under IFC schema 2x3 where sensors were categorized as IfcDistributionElements hosted in designated spaces. Manual corroboration between this static dataset of objects representing sensors, and measurements from those objects real-world counterparts was required to match these, using unique identifiers for each sensor and dataset.

C.4   Discussion & conclusions

The concept described here indicates the potential for storing dynamic building energy performance data within an existing IFC format. Such a system would link the operational and design phase of a building's life-cycle, enabling much closer scrutiny of the often referenced "performance gap". A conceptual data flow model for this system is shown in Fig. C.10.

The requisite actions to enable such a system must overcome the limitations considered through the examination of the IFC format and data types available from both pre-construction simulation and post-construction measurement.

C.4.1   Challenges to data management using IFC

Size of performance datasets

Time-series performance data (representing any variable aspect of a building's energy performance) can consist of several thousand data points, where a single variable measured
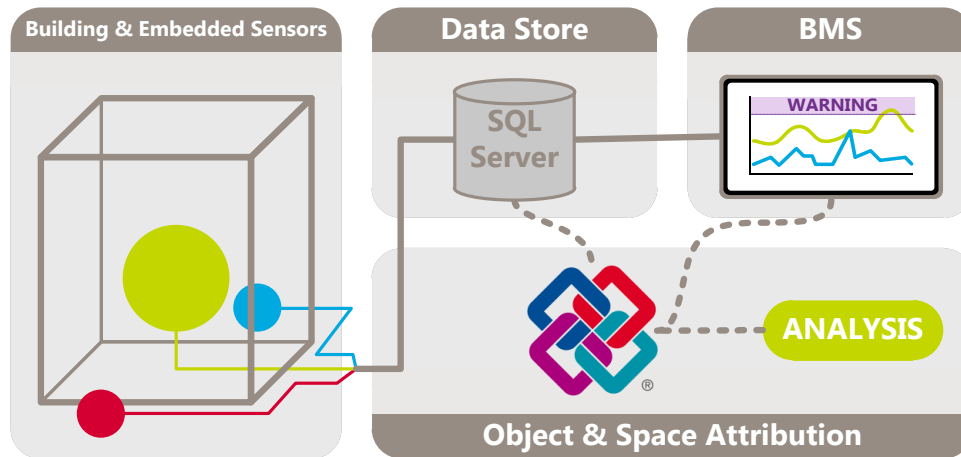
Figure C.10: Conceptual data flow model for IFC building performance monitoring and analysis

at 15 minute intervals for a full year results in over 3.5×10^3 values. Assuming each value is no larger than 255, each measured value should take up 1 byte, resulting in 35kB for this full year's results. The number of sensors required to monitor multiple aspects providing valuable performance information, and the number of sensors and frequency of reporting intervals means historical performance databases can become vast. These values may result in datasets less than a Gigabyte; however, computing power available currently still cannot manage this much data in conjunction with an IFC viewing tool, nor would the IFC be shared as easily due to its increased file size.

Accuracy of data/model representation

As was previously discussed, the purpose of an IFC is to store information about a building and its constituent objects and systems so information between different modelling platforms can be shared. Access to this information relies on the software's ability to read it from the IFC and display it in a suitable format. In addition to technological capabilities, the ability to access information is highly dependent on the skills of the person creating the model. In an attempt to create a life-cycle BIM, Hitchcock et al. (2012) found inconsistencies between modelling methods, differences between levels of detail and quality across a selection of models. These primarily originate from the ability of the modeller to create models of requisite quality and content, followed by the capabilities of the tool to model this.

Data access and management

Utilising existing datasets for the management of ongoing performance requires access to those datasets and management of them into a form suitable for their analysis. Existing datasets currently employed to record historical performance data store this data in SQL expressions, retrieved via queries. Understanding which field relates to which sensor or time series point is essential to accurately translate this information to a usable format.

C.4.2 Next steps

Scope exists for using a BIM environment to support the management of ongoing building performance data, using data storage mechanisms currently employed in cross platform data exchange. To achieve this changes would need to be made to existing IFC data storage schema time-series performance data can be attributed to objects and spaces within the BIM.

The first challenge would be the management of large sets of performance describing data, accounting for thousands of readings throughout a building, and giving insight into its operations, conditioning and overall performance. Using IFC as the basis for large dataset management is currently infeasible given current computational capabilities; however, use of IFC as a reference library to which various uses can reference may be more suitable. Using the objects modelled in this format as the basis for a relational database between design purposed BIM and in-use operational activities would lessen the performance gap through linking historical and live performance metrics with the objects contributing to them. Current BMSs do not adequately link the management of environmental conditioning with the design intent and management of equipment or spaces. Relating design data directly to in-use performance data offers the opportunity to investigate building performance aspects in greater detail, using as-built models to support these continuous commissioning actions.

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D   Paper 4

Gerrish, T., Ruikar, K., Cook, M. J., Johnson, M., and Phillip, M. (2017). *Analysis of basic building performance data for identification of performance issues.* In: Facilities 35 (13/14). DOI: 10.1108/F-01-2016-0003.

Analysis of basic building performance data for identification of performance issues

T. Gerrish, K. Ruikar, M. Cook, M. Johnson, M. Phillip

Purpose – The aim of this paper is to demonstrate the use of historical building performance data to identify potential issues with the build quality and operation of a building, as a means of narrowing the scope of in-depth further review.

Design/methodology/approach – The response of a room to the difference between internal and external temperature is used to demonstrate patterns in thermal response across monitored rooms in a single building, to clearly show where rooms are under-performing in terms of their ability to retain heat during unconditioned hours. This procedure is applied to three buildings of different types, identifying the scope and limitation of this method, and indicating areas of building performance deficiency.

Findings – The response of a single space to changing internal and external temperature can be used to determine whether it responds differently to other monitored buildings. Spaces where thermal bridging and changes in use from design were encountered exhibit noticeably different responses.

Research limitations/implications – Application of this methodology is limited to buildings where temperature monitoring is undertaken both internally for a variety of spaces and externally, and where knowledge of the uses of monitored spaces is available. Naturally ventilated buildings would be more suitable for analysis using this method.

Originality/value – This paper contributes to the understanding of building energy performance from a data-driven perspective, to knowledge on the disparity between building design intent and reality, and the use of basic commonly recorded performance metrics for analysis of potentially detrimental building performance issues.

D.1   Introduction

Management of a building's operational performance for the purpose of providing a comfortable environment for its occupants is one of the primary aims of Facilities Management (FM). The inhabitants of a building are its end-users, and those who are most likely to notice when a particular aspect of its environmental conditioning is not performing to specification. In addition to occupant feedback, the most commonly used method of monitoring building performance is through use of Building Management Systems (BMSs), comprising a network of sensors, actuators and control system for the conditioning systems, with access to records of various aspects of a building's performance. The modern BMS is used to control systems for optimal energy use and occupant comfort, indicating current performance of equipment and spaces; however, review of historic information to support energy use reduction efforts is less likely to occur, though becoming more common (Arditi et al., 2015).

Making use of the amount of information generated by a building throughout its day-to-day operation provides the opportunity to explore patterns of energy consumption, variation of temperature in response to internal gains and external weather, and the ability

to identify where potential improvements may be made. While this may not be considered "Big Data", the amount of energy used in the heating of non-domestic buildings within the UK accounts for 50% of the total energy consumption by these buildings (Waters et al., 2015). During 2010, UK commercial offices used over 14,000GWh, of which even small improvement in holistic building performance could yield significant reduction.

Identifying where improvements could be made here is possible at small scale using data collected during building use and continuous commissioning taking account of changing needs for heating, cooling and ventilation. Exploration and analysis of basic datasets describing building performance is commonly used to identify patterns of use, but analysis of these to provide insight into long term trends imperceptible to visual inspection may provide a valuable source of intelligence in the management and improvement of ongoing building performance. As monitoring becomes more commonplace (Ahmad et al., 2016; Clements-Croome and Johnstone, 2013), the opportunities to do so increase, and so does the availability of datasets to indicate where improvements could be made.

D.1.1   The performance gap

The difference between how a building should perform according to its design specifications and how it does perform is widely known as the "Performance Gap". The reasons for this gap have been extensively researched (Zero Carbon Hub, 2013; Menezes et al., 2012; Bordass et al., 2001), leading to a greater understanding of the interaction between user and building, methods of providing a comfortable internal environment and education of the occupant to make effective use of a building and its controls. These factors are changeable through behavioural modification and changes to operational strategies (Martinez-Molina et al., 2016), whereas less behaviourally modifiable reasons such as the reduced quality of as-built fabric are more difficult to identify or change following construction (Way and Bordass, 2005). In the report made by (Zero Carbon Hub, 2013), among all potential reasons for this "gap", build quality is included of which four priorities were targeted to reduce discrepancy between prediction and use. These were:

– Limited understanding by the designers of the requirements for a thermally efficient building (particularly in regard to detailing);
– Procurement of inadequately skilled labour resulting in poorly finished detailing, leading to air tightness and thermal bridging issues;
– Substitution of products on-site leading to less thermally efficient materials and improvised modifications detrimental to fabric performance; and
– Poor fabric installation potentially raising the U-value by up to 250% (Hens et al., 2007).

Research by Theodosiou and Papadopoulos (2008) showed that thermal bridging contributed to greater heat losses than otherwise encountered in spaces without such construction defects. Doran and Carr (2008) demonstrated that following retrofitting of insulation in poorly insulated residential buildings, the internal and external temperature difference increased by approximately 0.5°C. These studies examine in depth the effects of thermal bridging and insulation on space temperatures, but both required extensive investigation and monitoring of specific elements within those spaces and therefore a significant amount of effort in implementation and analysis (White, 1989). These investigations

may be considered a form of Post-Occupancy Evaluation (POE), where instead of using long-term building performance data, short-term yet high-resolution monitoring is used to determine fabric element performance. In these studies the amount of heat lost through these thermal bridges is often greater than expected (Marincioni et al., 2015), but slight variation in building fabric quality may not be shown through visual inspection of records without access to thermal imaging equipment.

D.1.2   Post-occupancy evaluation

Investigation of monitored building performance information can provide a means of understanding of the reasons behind why a building performs as it does, indicating potential faults and opportunities for improvement (Menezes et al., 2012). The process of investigating this data, among evaluation of the ways in which the building is used and how its occupants feel within it, is the purpose of POE, with a view to better managing building systems operation for improvement in efficacy and in many cases managing occupant expectations (Brown and Cole, 2009). In the UK, POE has been referenced in recent initiatives to improve in-use operational efficiency as part of a Soft Landings policy (Way et al., 2009), but while the handover of a building and proper operation of its systems contribute to the overall performance of the building, the building's fabric plays a large part in this performance. Most POE studies identify the factors contributing towards poor building energy performance (Bordass et al., 2001), demonstrating the main reason in most cases to be improper use of the building systems and spaces (Pegg et al., 2007). Additional schemes to utilise the evaluation of buildings in a larger context to identify trends are also implemented (The AECB, 2013; The Digital Catapult and Innovate UK, 2016; DOE et al., 2016), but again focus on holistic performance without aggregation of datasets in which these performances could be contextually analysed. While construction quality is mentioned as a contributing factor to potential performance defects from designed expectations, methods of identifying where fabric may be causing a significant effect on internal conditions (and therefore energy used to condition these spaces) are limited.

Currently the main methods of identifying where faults in construction, or the effect that expected wear and tear throughout a building's use contribute towards a potential deficit in performance (Mydin et al., 2012) are walk-round surveys and continuous operations and maintenance records. Building fabric inspection during walk-round surveys and the use of thermography to identity cold-spots where thermal bridging, insufficient or deteriorated insulation may be present (Taileb and Dekkiche, 2015) take time, and given the need to further investigate each potential problem can become a major inhibitor to the full evaluation of a building during POE (Preiser, 2003). In some cases, problems may be missed due to inaccessibility, for example in non-visible or difficult to access areas such as roofs, or behind cladding. However, even technology such as thermal imaging cannot see through walls, and rely on emitted radiation for which, in cases such as thermal bridges around glazing, may not be easily identifiable (Fox et al., 2014). In these situations, the measurement of descriptive space performance aspects is often the next step in identifying why a performance characteristic is being perceived, and where "big data" style analytics could be applied to historical building performance records to provide useful insight.

D.1.3 Performance monitoring and interpretation

Monitoring of space temperatures in conjunction with knowledge of a building's operational strategy can indicate where potential issues in those monitored spaces may be occurring. For example, a space that does not increase in temperature during a period where the heating in that space is active could indicate a closed valve, a non-responsive sub-system or faulty sensor (Ahmad et al., 2016). Within a large building where there are likely to be several sensors recording multiple aspects in each monitored space, including monitoring of Heating, Ventilation and Air-Conditioning (HVAC) equipment, and extracting meaning from such expansive datasets can become difficult (Zhou et al., 2016).

Many difficulties occur when accounting for errors. Typically, a problem with the building is reported, requiring investigation to which historical monitored performance is referenced (Kim et al., 2009). Knowing the location of a potential issue enables the investigator to narrow the review of records to adjacent and related areas, shortening investigation time. If the issue is not identifiable in this way (or is too slight to give a clear distinction of under-performance), there is very little the investigator can use to remediate that performance inhibitor (Djuric and Novakovic, 2009).

Use of BMS performance records to suggest opportunity for performance improvement demonstrate this problem well. A building may be monitored across all measurable metrics; however, without a defined scope in which potential issues can be identified, there is less likelihood of distinguishing normal levels of performance from that outside reasonable expectation (Seem, 2007). Lessons may be learned from outside construction subjects, where Levac et al. (2010) suggests that clarification of purpose, process and interpretation can maximise the usefulness of analysis. Here, automatic recognition of faults and errors are useful in areas where the range of expected monitored variables is known, and in which patterns and trends can be quantified. Fault Detection and Diagnosis is prevalent in HVAC equipment monitoring (Capozzoli et al., 2015), but in space temperature monitoring there is limited research due to the number of factors contributing to a building's thermal response. Pattern recognition can however be used to suggest potential faults where the user does not know where to start, if the data used is extensive enough for some patterns to be found (Peña et al., 2016).

Automatic recognition of errors in building conditioning have been developed (Khan et al., 2013; Katipamula and Brambley, 2005), but these mostly apply to specific pieces of equipment where ranges of expected operation are given, outside of which an alarm is triggered. Similarly, spaces can be monitored where excess temperature triggers an alert to the FM to investigate, but these are less common given that building services monitoring would likely preclude this via measurement of the systems providing those conditions. Long-term monitoring overlooks faults with building fabric that may have little immediately identifiable effect on energy consumption, but contribute to excess energy consumption. For example, an individual space using significantly more heating than others may not be recognised as part of regular monitoring as it may be only part of a group of spaces, or where changes are subtle and performance reduction is not noticed.

In addition to unrecognised errors, gaps in data is another area where limits are imposed on analysis of space temperature performance. Baltazar-Cervantes and Claridge (2002) demonstrated means of rectifying errors in time-series temperature records, with Hu et al.

(2014) furthering this for longer term gaps. As technology now allows for monitoring and storage of longer term records (Yu et al., 2015; Kim et al., 2011), gaps in data become less impacting given the breadth of context made available. Through aggregation of records and accessibility of larger descriptive datasets, the potential for errors and gaps increases, but are also more discountable due to the range of data with which to compare. However, with that larger amount of data, analysis is also then susceptible to interpretation errors such as confirmation bias and causation/correlation misrepresentation (Taleb, 2013).

D.2 Method

The relationship between internal and external temperature, and the difference between these are investigated, using the rate of change for each to derive potential construction quality or internal conditioning issues within of the monitored spaces. In this approach, historical records describing space temperature data are used to show the rate of change of the rate of change in temperature over time, as a function of the difference between external and internal temperature. While this is limited to periods outside normal conditioned hours (as during occupied hours occupants, lighting and equipment use can alter internal temperature significantly), it shows a subtle distinction of spaces under and over-performing in terms of their heat loss.

D.2.1 Test cases

Three buildings were used in the development and testing of this method, demonstrating its potential and limitations. Each building is a different type (domestic, non-domestic office and non-domestic school), in which operating conditions and schedule differ significantly given their purposes. Each has temperature monitoring within several spaces, providing a record over at least 1 full year and external temperature recorded on each site to provide external context. These buildings were chosen primarily due to availability of their internal space temperature data, and as a range of test cases in which the method could be evaluated against varying conditions. These were: limited number of monitored spaces; differences in occupied hours; location and external temperature variation conditions; and method of heating, cooling and ventilation. Floor-plans for each of these buildings are given in Fig. D.1, with monitored spaces labelled.

Residential

The residential building is a 3-storey dwelling located in south-east England, recently refurbished to provide greater insulation, airtightness and heating system efficiency. Hours of operation (where occupied and assumed heated) were between 17:30 and 09:00. The composition of this building is typical of residential buildings in the UK, comprising non-insulated cavity walls, though during refurbishment this was supplemented with expanded polystyrene added to the external cladding with space heating provided by a gas central heating. Data for this building was available for a full year (June 2012 – May 2013) at hourly intervals. Previous studies by Dowson (2012) on this same building showed an improvement in performance following refurbishment, though this was less than expect in some areas potentially due to poor construction quality. Thermal bridging was also
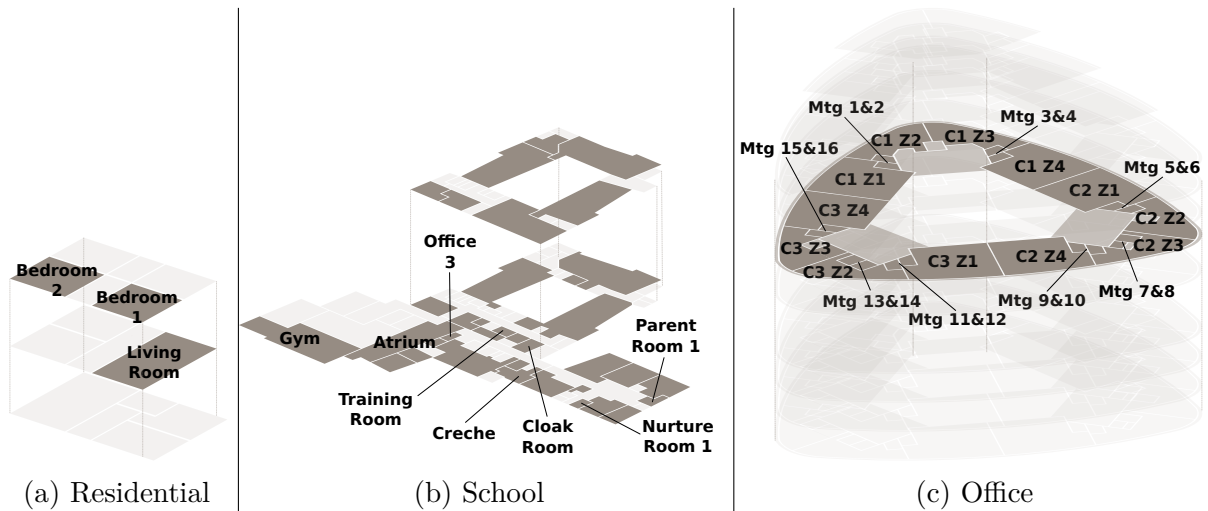
Figure D.1: Evaluated building floor plans

identified in the Living Room space using thermography, showing the link to the adjacent house as point of greater than usual heat loss.

School

The school building is a primary school completed in 2014 and located in the north of England. This building received a Building Research Establishment Environmental Assessment Method (BREEAM) "Excellent" rating and comprises a 2-storey conventional rain-screen clad, brick and mortar naturally ventilated building with spaces dedicated to teaching, childcare and administration. Occupied hours were between 08:00 and 18:00, heated correspondingly with a ramp-up period from 07:00. Data for this building was available for 19-months (September 2014 – April 2016) at 15-minute intervals. A full POE is being conducted on this building after occupants described problems with overheating and trouble maintaining stable temperature in several spaces. During a preliminary walk-round survey, no immediately visible problems were noted indicating that the rooms were improperly conditioned, nor were there behavioural issues noted such as interaction with equipment or window opening when that would cause such problems.

Office

The office building is a high performance office located in the north of England and completed in 2013. It comprises 14-storeys (of which 9 are repeated floor-plans) and utilises a double-skin façade to minimise solar gain during summer and provide a means of preheating supply air during winter. The building is occupied between 08:00 and 19:00, with heating provided via conditioned air through plenum Variable Air Volume (VAV) boxes into perimeter heated spaces, and passive chilled beams for cooling. Each repeated floor comprises mainly of open-plan spaces, with meeting rooms and small server rooms around a central atrium, into which cross-ventilation was planned during design. Data was available for this building at 30-minute intervals between August 2014 and March 2016. All spaces were monitored throughout the building; however, in several, errors in recording meant data was unsuitable for analysis resulting in a subset of the total spaces

where data was available being used.

D.2.2   Data collection and processing

Prior to data analysis, significant amounts of pre-processing were undertaken to ensure the data was suitable for analysis without potential for erroneous records to influence results. Python was chosen as the language used to parse, transform and output results from the historical temperature records, using the Pandas package (McKinney, 2010) due to its time-series data handling capabilities.

For each building the time-series data was sorted according to its time-stamp and re-sampled to a common interval. For example, where records logged non-uniform interval data, this was made uniform with the corresponding values linearly interpolated to fit. In all buildings, the data was re-sampled to half-hourly intervals for ease of comparison, and where gaps larger than 2-intervals were found these were left null to prevent incorrectly estimated data impacting the analysis outcome. Errors, such as values outside reasonably expected limits due to faulty or incorrectly calibrated sensors, were accounted for by removing values outside the winsorised mean between the 10th and 90th percentiles ± 10 standard deviations.

Seasonality was not accounted for here, meaning any time periods where there were a disproportionate representation of different seasons (for example, where data represented one winter and two summer periods) was not tested for; however, given the number of individual days in which the following method was applied this, would have little effect on the outcome.

Temperature difference/change in temperature difference

The difference between the internal (T_i) and external (T_o) monitored temperatures is the basis of this analysis. While external temperature drops, the amount of energy required to maintain a specific internal temperature above the outside value under the same level of internal gain increases. In this analysis, we are not looking at energy consumed by HVAC systems, only the response of the room once these systems have been switched off. Therefore, after completion of the analysis, the hours used to identify potential differences in space composition or use are limited to those directly after heating (as all buildings here are in a primarily heating-based climate) has been switched off.

A typical daily room temperature profile for the school is shown in Fig. D.2 compared with external temperature, showing that as the heating switches off at 18:30 (and cleaners leave shortly after this at around 19:15) the internal temperature drops in proportion with the drop in external temperature. This is primarily due to losses through fabric in conjunction with loss to adjacent, cooler spaces within the building. If the building is uniformly conditioned and of the same composition and construction quality throughout, each space would be the same temperature at this point, meaning an externally adjacent space would lose heat faster than internal spaces. In the figure, a sharp drop in internal temperature can be seen on May 20th, most likely as a result of an open window, demonstrating the impact of user behaviour on the monitored conditions within a space. Conversely, the lack of user interaction in unheated spaces over the weekend, show the gradual loss of heat through conduction and infiltration as the space returns to ambient conditions.
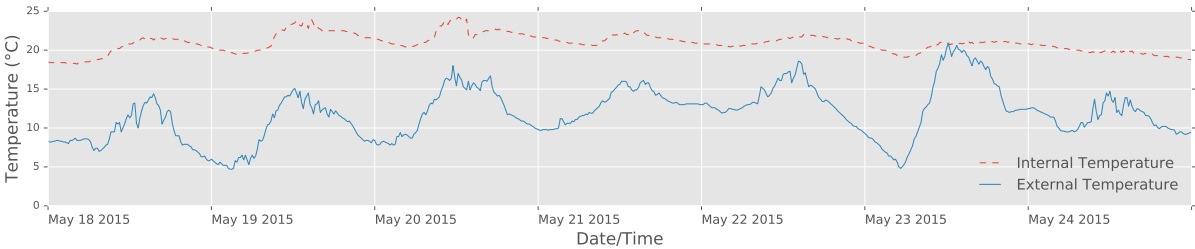
Figure D.2: Typical diurnal internal temperature response to external temperature and HVAC conditioning (for School Base Room 5)

For all monitored rooms, the difference between internal and external temperature at each point in time sampled is calculated. As these tend to vary greatly due to the variability of both internal and external heat gains and losses contributing to this difference, the rate of change over time is also calculated using the gradient of this temperature difference (Fig. D.3). Decreasing the interval between sample points would smooth these results, but for the purposes of testing, a high sample rate is useful due to the potential for inclusion of cumulative errors. The most important part of this data is the period after the conditioning is switched off, in order to understand each monitored rooms response to a steadily decreasing external temperature.
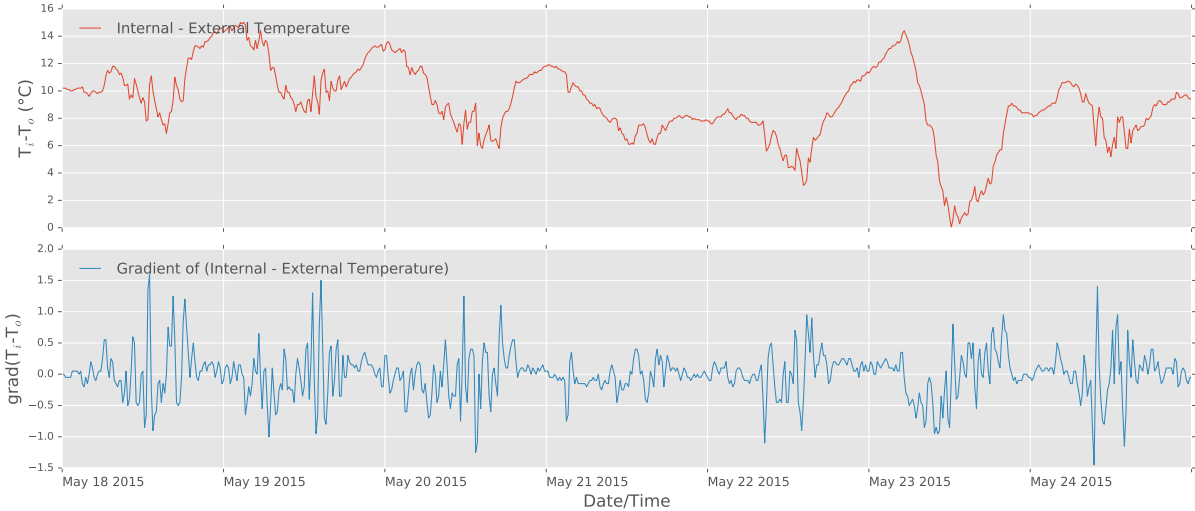
Figure D.3: Difference between internal and external temperature and the rate of change at each time-step (for School Base Room 5)

Fig. D.4 shows a changing relationship over the course of the day by plotting these two values against each other for each sampled time. During occupied hours when heating is on and spaces are being utilised, the majority of spaces maintain a constant internal temperature against a gradual change in external temperature. This results in a wider spread in these plotted points, and conversely a narrower spread after the heating is switched off, when the rate of change in internal temperature is a proportion of the rate of change in external temperature. Generally a drop in temperature inside coincides with a drop in temperature outside, but in some cases where internal gains are present this can be seen as a wider spread of points during unoccupied or unconditioned hours.

Figure D.4: Scatter plot showing the gradient of the difference in temperature plotted against the difference in temperature at the same point in time (for residential living room)

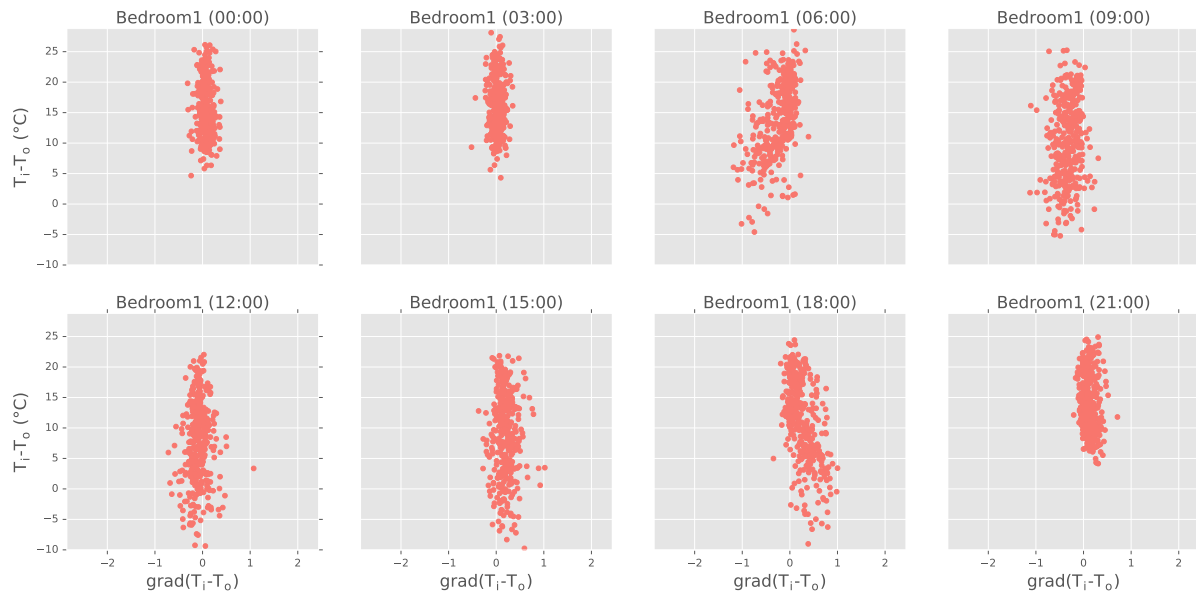Two mechanisms are being presented in Fig. D.4, showing that during cool-down hours (06:00-09:00 in the residential example), the greater the difference between internal and external temperature, the greater the rate of change in that temperature difference over time. During heat-up hours (18:00-21:00 in the residential example), the inverse is true meaning the rate of change in temperature difference is greater at lower temperature differentials.

Average rate of change of temperature

For each room and at each sampled time, a slight relationship can be found between temperature difference and rate of change during times at the start of, and following conditioned hours. For each time period relationship illustrated in Fig. D.4, the average slope between all points gives a value for the rate of change in temperature that room experiences, as a function of the internal/external temperature difference. A line of fit with gradient above 0 shows a space heating up, with an increasing gradient demonstrating a faster response to changing temperature. A line of fit with gradient below 0 shows a space cooling down, with the magnitude of that negative gradient describing the speed of thermal response. Generally, a room with no building services intervention would be expected to respond to a decrease in external temperature with a slight lag and rate of change that initially increases, then decreases. Those spaces with potential problems in their conditioning or fabric would show a different response to other monitored spaces in the same building.

Plotting the average slope of each time-step in Fig. D.4 for each space shows a clear distinction between those spaces responding differently to the temperature difference than the rest of the monitored spaces. Fig. D.5, Fig. D.6 and Fig. D.7 show how each monitored space in the three buildings compare with other spaces in the same building, in terms of their cooling and heating sensitivity to the rate of change of the internal and external

temperature difference. The key periods after heating has been switched off are those most interesting as they show the space's response to changing temperature difference without additional influence from artificial conditioning and are indicated. The analysis period shown in each plot contains the data from which further statistical analysis is performed. Spaces outside the general trend are those potentially warranting further examination, and are those highlighted on each plot demonstrating their thermal response amidst all other monitored spaces. Average internal and external temperatures are also shown for context, with a small error in Fig. D.7 where the air-handling system starts at 06:00 resulting in greater airflow around the sensor and a noticeable drop in perceived external temperature.
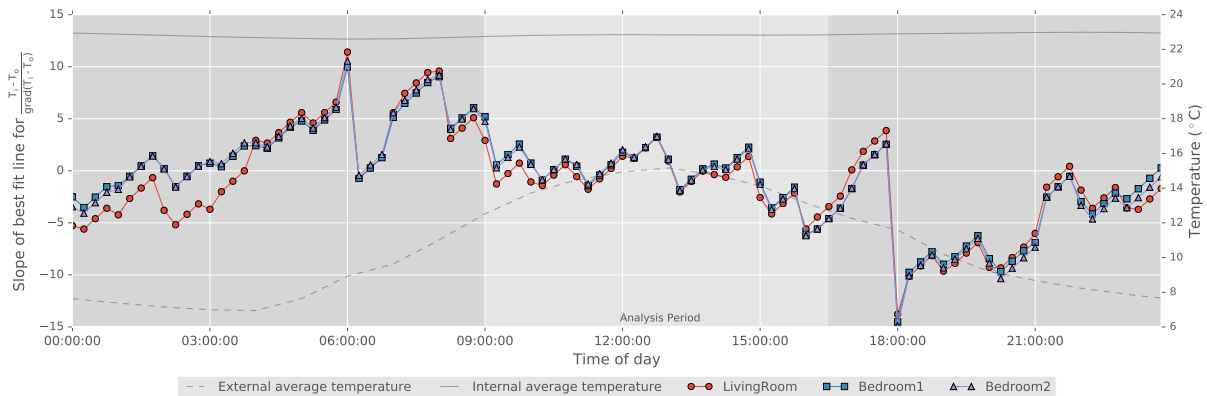
Figure D.5: Residential building thermal response
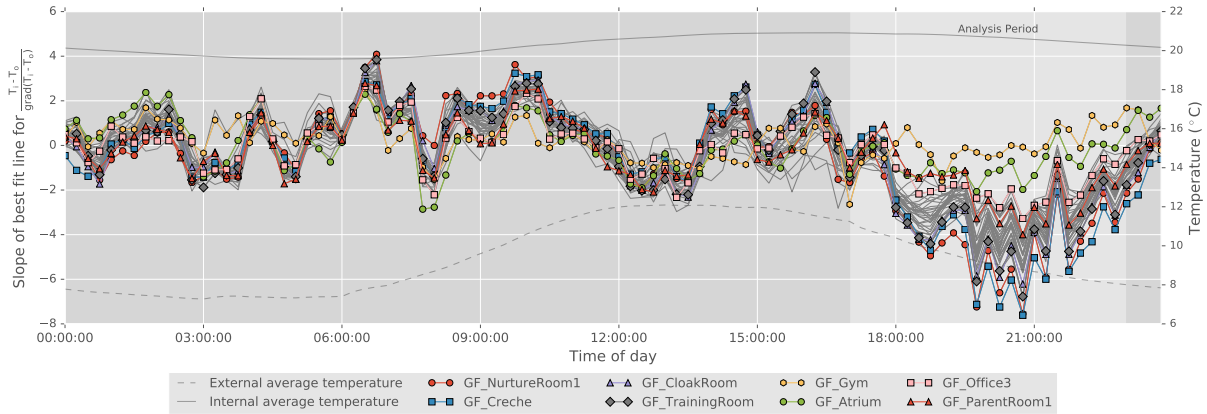
Figure D.6: School building thermal response

Fig. D.5 for the residential building shows that the Living Room (where thermography showed thermal bridging against an adjacent, less efficient building) is marginally more susceptible to changing internal/external temperature difference than the other two monitored spaces. Similar patterns can be seen in the school (Fig. D.6) in the Gym, Atrium and Parent Room 1, and in the office building (Fig. D.7) for Level 4 Meeting Room 8. These indicate that each space is losing heat at a rate greater than the average of all other spaces. In the school, several spaces show significant difference from the average thermal response, notably the Crèche and Nurture Room 1 where occupant complaints had been noted during the POE. As these lose heat at a greater than average rate after occupied hours, they behave more thermally lightweight in response to conditioning during occupied hours, suggesting potential overheating.

Figure D.7: Office building thermal response

The office building shows far lower variation in rate of temperature change during unconditioned hours as is to be expected given its double façade configuration mitigating against heat loss, and close control maintaining a setback temperature outside occupied hours. Spaces deviating from the normal pattern indicate another issue impacting that spaces temperature change, such as operational difference or change in use.

D.3 Results

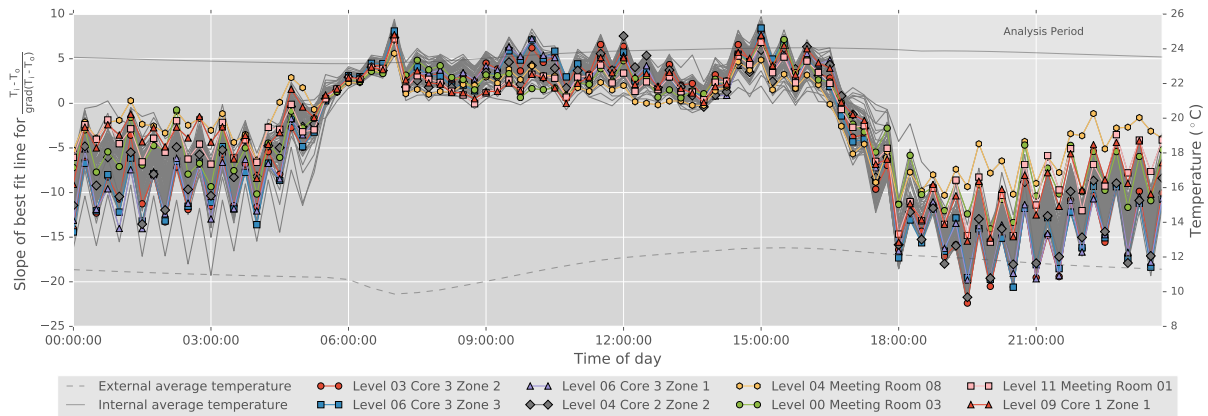As each room has a different purpose and use, each shows a slight difference from the average response of the entire building; however, those that are significantly different in terms of their response to changing internal and external temperature difference can be immediately identified. Each building is investigated to identify why these differences occur and determine whether the quantification of the values portrayed in Fig. D.5, Fig. D.6 and Fig. D.7 can be used to determine whether this difference is significant enough to warrant further attention. Quantification of difference is achieved through obtaining the average slope within the analysis period, for which linear regression is used to determine goodness of fit from those points within that period, shown in Table D.1.

Quantification of these results enable to investigator to quickly identify which rooms require most attention, using the average rate of change within the analysis periods. Confidence in the results shown so far has been overlooked in favour of visually comparing each space with the average. Arranging each monitored place in order of its average rate of change after occupied hours (when heating is switched off) shows those rooms where heat is lost at a greater and slower rate than others. The analysis periods here represent between 24 and 30 distinct measurements; however given the changeability of the slope within these points the R^2 value for set of data remain low. This is particularity so in the office where overnight conditioning maintains a set-back temperature, resulting in a rapidly changing slope. While closeness of fit is low, the slope average values indicate those spaces at the extremes of the thermal responses across all monitored spaces, and therefore those with the greatest and least sensitivity to changing temperature.

Table D.1: Average slope and R^2 for the analysis period

(c) Office (n=24)

Space	Slope Average	R^2
L03 C3Z2	-15.03	0.64
L06 C3Z3	-14.89	0.66
L06 C3Z1	-14.67	0.66
L04 C2Z2	-14.30	0.62
...	...	...
Average	-12.64	0.59
...	...	...
L09 C1Z1	-9.98	0.49
L11 Mtg1	-9.52	0.50
L00 Mtg3	-9.11	0.59
L04 Mtg8	-6.13	0.35

(a) Residential (n=30)

Space	Slope Average	R^2
Living Room	-0.70	0.29
Average	-0.33	0.19
Bedroom 2	-0.17	0.15
Bedroom 1	-0.11	0.14

(b) School (n=24)

Space	Slope Average	R^2
Nurture Room 1	-3.88	0.70
Creche	-3.78	0.75
Cloak Room	-3.27	0.70
Training Room	-3.25	0.68
...	...	...
Average	-2.41	0.66
...	...	...
Parent Room 1	-1.74	0.72
Office 3	-1.54	0.63
Atrium	-0.75	0.24
Gym	-0.06	0.09

D.3.1 Residential building

As only 3 spaces were monitored in this building, quantification of each spaces thermal response in comparison with the average of the whole building is limited. However, using the data in conjunction with previous in-depth investigation by Dowson (2012) some initial conclusions may be reached regarding application to small sample sizes. Fig. D.8 shows the two most extreme spaces from the overall average (taken from Fig. D.5), which show very little deviation from the average, except for in the Living Room where the space loses heat overnight and early in the day. This corresponds to the previous study finding of thermal bridging between the space and the adjacent building, and suggests the Living Room responds quicker to temperature differences than other monitored spaces.

D.3.2 School building

The two spaces at the extremes of the range of thermal responses in the school are plotted in Fig. D.10. The position of these spaces in the school building show that they are both externally adjacent, though respond differently to an internal and external temperature differential. The opportunity to investigate these spaces further allowed a walk-round and thermography survey to identify potential reasons for this difference.

In Nurture Room 1 two reasons for a greater than average heat loss during occupied hours were found to be thermal bridging at the junction between an internal and external wall, and its adjacency to a continuously mechanically cooled server room (Fig. D.9). The Gym was found to be conditioned outside normal hours due to its use after school hours
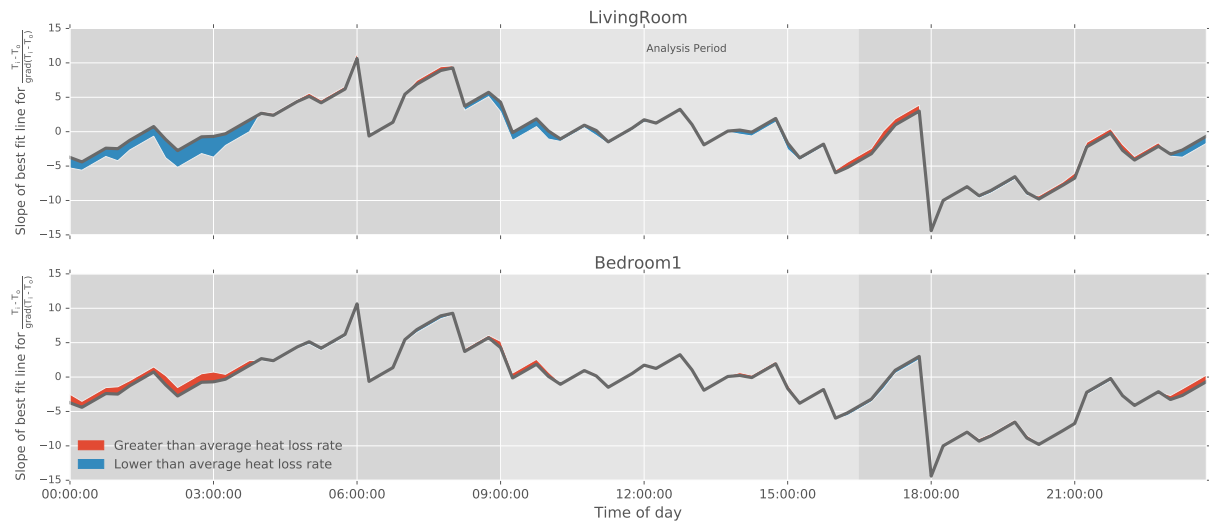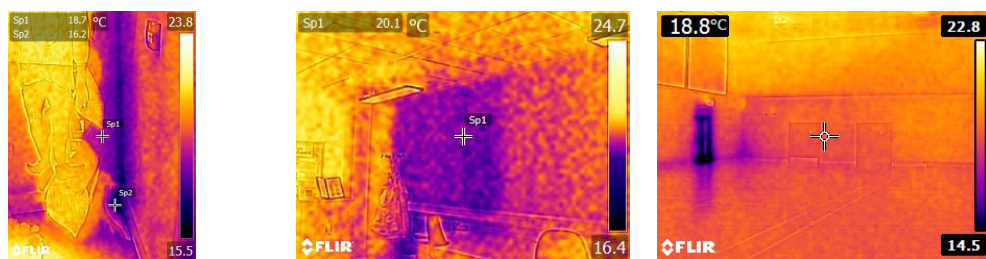
Figure D.8: Difference between individual spaces and average of the whole residential building

(a) Nurture Room 1: Thermal bridging

(b) Nurture Room 1: Cooled adjacent room

(c) Gym: Air leakage and slight thermal bridging

Figure D.9: Thermal images from school

for activities; and given its size and amount of airflow expected for a space of this type more closely matched the change in external temperature and greater than average rate of heat loss overnight.
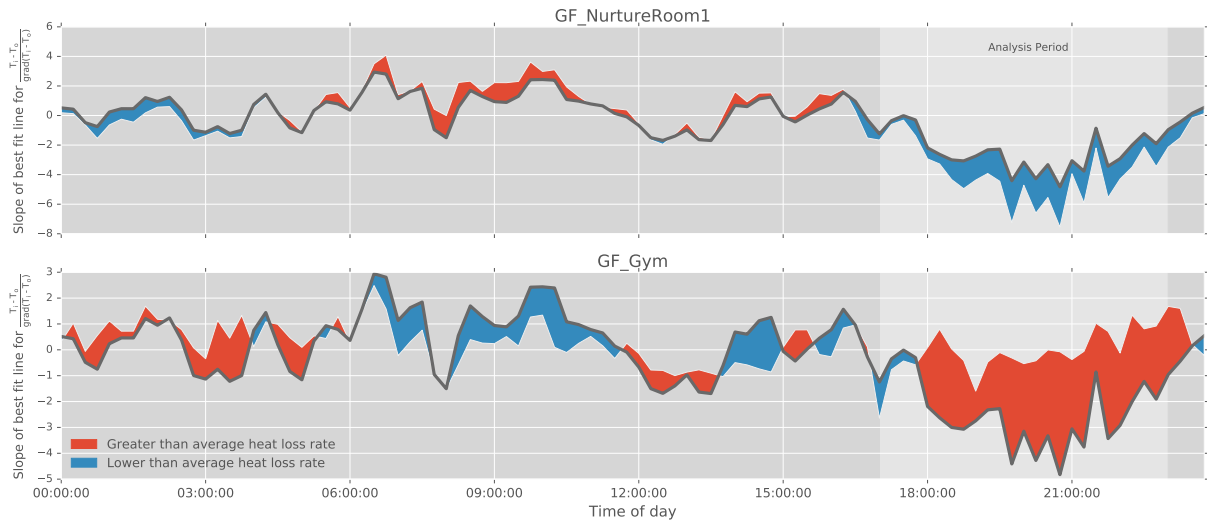

Figure D.10: Difference between individual spaces and average of the whole school building

D.3.3   Office building

Of the number of monitored spaces within the office, only 31% contained error free data suitable for analysis. This suggests the need for additional preprocessing of data containing errors to enable inclusion of a far greater number of spaces. However, the number of spaces monitored here is the largest of the building's evaluated, providing the most data rich environment in which the methodology is tested. The method of conditioning within the office is also of interest due to it use of mechanical ventilation providing a constant set-back temperature outside conditioned hours, shown in Fig. D.11 as the rapidly changing thermal response as internal temperature drops along with building services provision of heat to maintain that set-back.

Level 04 Meeting Room 08 shows a greater heat loss rate than the average for all rooms, which was further investigated using lighting and small power records and then visual inspection. Greater out-of-hours use of power within the space was identified as a result of changes in use, which were discovered to be the testing of electrocution equipment instead of intended use as a meeting space. This change resulted in mechanical heating and ventilation being required to keep this space at the set-back temperature, which in turn led to a perceived greater than average heat loss rate due to this conditioning compared with other spaces during a similar time period.

D.4   Conclusion

This basic analysis of internal and external temperature does not consider the equipment used to service the monitored spaces, the use of each space, nor does it allow the comparison between different buildings (as the average of the whole buildings performance is the metric
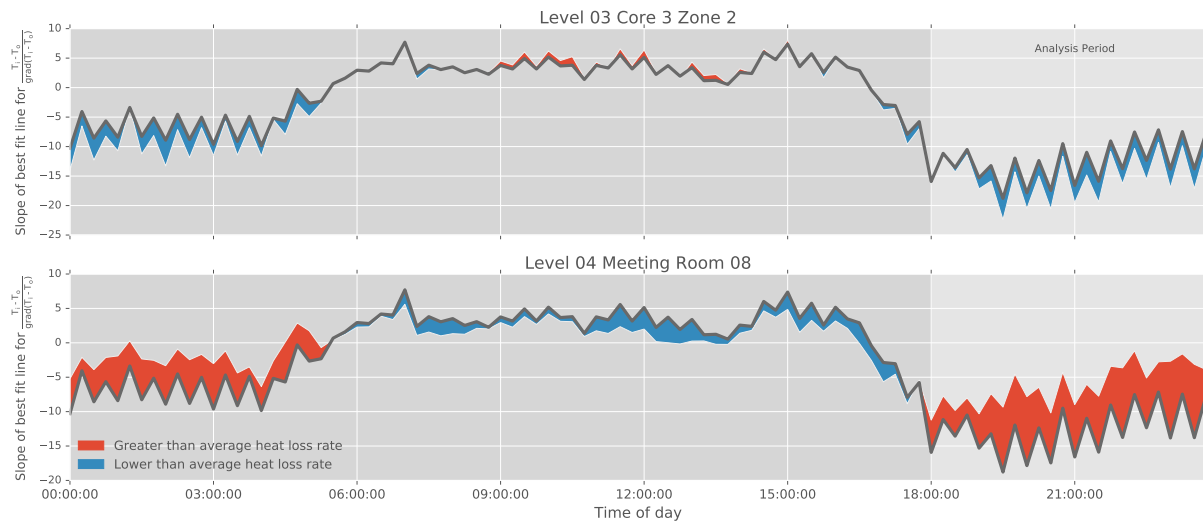
Figure D.11: Difference between individual spaces and average of the whole office building

by which space temperature comparison is possible). However, the basic information required for this analysis and the procedure described here demonstrate the potential for use of large sets of descriptive space temperature data to indicate where there may be issues in the fabric, conditioning or use of a space in context with that spaces heating and cooling provisions.

Temperature is one of the most commonly recorded performance metrics, meaning its application for analysis is more likely than equipment performance data that many buildings would not have access to, nor have implemented. As part of the information making up what is truly "Big Data", basic data analysis can be used to provide a more thorough understanding of a building's behaviour and demonstrates opportunities to improve building performance through recommissioning of building services, calibration of sensing equipment and remediation of poor fabric detailing. A key requirement of analysis is that the data used is accessible and representative, which was found to be a major limitation in this study. Of the total number of sensors from which data could have been obtained in the office test case, only 31% were found to be usable due to incorrect calibration, errors in reading and non-reporting.

Comparison of alike rooms shows variation across their response to changing internal and external temperature differentials, indicating that there is potential for these differences to be further investigated and identified. For example, the three spaces in the office with the greatest rate of heat loss are on its windward side, which should not impact their performance given its double façade configuration. This indicates that there may be an issue with the construction quality on this portion of the façade.

The limitations of this particular procedure have been given, but improvements to the process which could also be applied to other descriptive building performance data are as follows:

– Analysis of data over longer time periods would give a more clear and valid value for each spaces temperature difference/gradient of temperature difference. This could however also bring additional uncertainty as spaces and building services provisions may change over time;

– Higher resolution datasets would enable more confidence in the values calculated, especially in the comparative ranking of spaces;

– Basic reasons for the differences in slope have been identified as differences in internal gains between monitored spaces, potential fabric problems, locations within the building and mechanical conditioning. Grouping analyses into spaces externally adjacent should show more clearly where problems such as thermal bridging and poor insulation are most likely. In buildings where spaces are internal only (such as the office used here) or those where there are limited number of externally adjacent spaces, a large difference between spaces may not be seen;

– Rather than ranking an individual spaces performance based on the slope of points within its analysis period, the average difference between the space and the average for all monitored spaces may give greater indication of performance disparity; and

– Application to other descriptive datasets could show where equipment or services are being used ineffectively. For example, daylight dimming controlled lighting could be assessed using lighting load and external illuminance levels to show the relationship between lighting power demand and available natural lighting.

Future work will integrate this method of assessment into a Building Information Modelling (BIM) supported tool, utilising BMS output and an as-built model containing as-designed performance information, providing a method of evaluating a building against its intended performance.

Acknowledgements

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E   Paper 5

Gerrish, T., Ruikar, K., Cook, M.J., Johnson, M., Phillip, M., Lowry, C (2017). *BIM application to building performance visualisation and management: Challenges and potential.* In: Energy and Buildings 144. DOI: 10.1016/j.enbuild.2017.03.032.

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

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This paper evaluates the potential for use of Building Information Modelling (BIM) as a tool to support the visualisation and management of a building's performance; demonstrating a method for the capture, collation and linking of data stored across the currently disparate BIM and Building Management System (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 behavioural and methodological 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.

E.1 Introduction

The service sector accounts for 20% of UK energy consumption (BEIS, 2015), with UK government targets for reduction of CO_2 emissions of at least 60% relative to 2006 levels by 2050 (DTI, 2006). 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 Building Information Modelling (BIM) implementation on publicly funded projects in the UK is a contributor to this target (Cabinet Office, 2011), driving the development of efficient buildings through improved design coordination, and management of design and operations information (Tuohy and Murphy, 2015).

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 (Scopus, 2016). In an industry still attempting to close the recognised performance-gap between predicted and measured building performance (Menezes et al., 2012), methods of assisting in this process are encouraged (Tuohy and Murphy, 2015), and where BIM is conveniently present as a platform on which to develop these.

Yalcinkaya and Singh (2015) 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 (Facilities Management (FM)) use (Codinhoto et al., 2013; Volk et al., 2014) via model view definitions and export from design models (East et al., 2013), supported by development of open exchange formats (Laakso and Kiviniemi, 2012). While useful and necessary for efficient management of building and its systems (RICS, 2011), accessibility to information does not necessarily mean that information will be utilised, nor does it guarantee effective performance management (Tribelsky and Sacks, 2010).

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.

E.2   Background

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 (2005), 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. (2014), 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 (Tuohy and Murphy, 2015) 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 (Gerrish et al., 2014). Disparity between the schools of thought on adopting BIM for niche purposes is demonstrated between Kiviniemi (2013), who proposes the client as the driver for adoption of BIM, and Howard and Björk (2008), 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.

E.2.1 Drivers and barriers of wider implementation

Cao et al. (2016) 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 (Tuohy and Murphy, 2015). Application of BIM for building performance management has been explored by Srinivasan et al. (2012) and Göçer et al. (2015), 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. (2013) 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. (2013) 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.

E.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 (Yalcinkaya and Singh, 2015). Previous examples of this have been demonstrated to benefit the building's end-user through reduction of errors, lead times and cost in design and construction (Becerik-Gerber and Rice, 2010); however, practical application in the optimisation of building energy performance is less widespread.

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. Che et al. (2010), demonstrate the use of BIM in this manner, prompting the development of exchange methods between BIM and energy performance simulation tools

(Hitchcock and Wong, 2011), and the analysis of predicted performance (Stumpf et al., 2011), 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 (Torcellini et al., 2004) and inaccuracy of predictions (Turner and Frankel, 2008).

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 (East, 2007), describing the composition of the represented buildings systems (Elmualim and Pelumi-Johnson, 2009) and operation (Korpela et al., 2015). 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 (Moon et al., 2013; Pang et al., 2012; Wetter, 2010; Bazjanac, 2008).

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 (McGraw Hill Construction, 2014), where BIM may be utilised to improve existing processes (Way et al., 2009). 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 (Thabet et al., 2016).

E.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 (East, 2007). The same environment federating multiple discipline designs has also been used to store maintenance information (Motawa and Almarshad, 2013; Korpela et al., 2015), for storage of system operation documentation (Elmualim and Pelumi-Johnson, 2009), and demonstrating BIM as an environment through which meta-data could be accessed and exchanged (Khaja et al., 2016). 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 (Shelden, 2009).

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-1990's propagating the data infrastructure underpinning the information age are now being applied to construction via big-data analysis (Zhou et al., 2016; Mathew et al., 2015) and BIM (Rooney, 2011).

Haas et al. (1997) 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 (Laakso and Kiviniemi, 2012)), where relational systems rely on middle-

ware to support specific functionality interpreting and utilising the related information effectively. But data relation during both design (Gerrish et al., 2014) and operation is challenging due to the technical difficulties in linking disparate systems (Tomašević et al., 2015) and requirement for common standards (Corry et al., 2015).

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 (Volk et al., 2014). Further guidance is required for BIM enhanced performance management in this area, outside the context of asset management and maintenance, simulation and fault detection.

Performance management efforts and standards

CIBSE (2012) and ASHRAE (2006) 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 (Project Haystack, 2016) provides a Building Management System (Building Management System (BMS)) data model for the structuring of information related to equipment performance management and Open Building Information Xchange (oBIX) (OASIS, 2016), 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 Extensible Mark-up Language (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 (Gerrish et al., 2015).

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.

E.3   Linking BIM and operational performance

The method presented follows the latter-stages of design development, and subsequent handover and operation of a 30,500m^2, 3000 person non-domestic office building completed

in 2013 (Fig. E.1). Developed prior to widespread BIM implementation, the information available describing the building, its constituent systems and performance were held in disparate un-federated design models and documentation from various disciplines, representative of the majority of data describing buildings in-use currently (Volk et al., 2014). 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. 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.
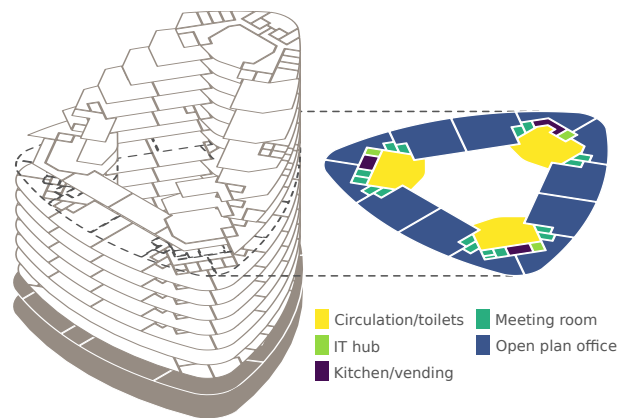

Figure E.1: Case-study building representative floor-plan

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 (Sommerville, 2010, pp. 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 E.1. These are typical of commonly used software platforms used during building performance design and operation, except for the BMS front end and Python, which were the means through which data interoperability and interpretation was achieved.

E.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

Table E.1: Software used during development of the BIM-linked performance monitoring method

Software	Function
IES-VE (Integrated Environmental Solutions, 2016)	Modelling and simulation of building performance
Autodesk Revit (Autodesk, 2015b)	Modelling and attribution of descriptive performance meta-data to objects & spaces within the BIM model
Autodesk Dynamo (Autodesk, 2015a)	Attribution of simulated performance output to Autodesk Revit model
	Extraction of geometry and meta-data from Autodesk Revit into a lightweight data-interchange format (JavaScript Object Notation (JSON))
Python (Pandas (McKinney, 2010), Matplotlib (Hunter, 2007),	Extraction of data from BMS Structured Query Language (SQL) Server
	Cleaning of extracted data
ipywidgets (Pérez and Granger, 2007))	Code interlinking JSON file with query-able performance data

(Shermer, 2014); however, given the need for creation of a model and further investigation of the building, potentially incomplete, inaccurate and disorganised information (Thabet et al., 2016) could be disregarded. With increasing information generation during design and operation an inevitable result following more widespread use of digital modelling techniques (Hung-Ming et al., 2016), the amount of information being generated using BIM requires effective management

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 building's 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 (Volk et al., 2014).

Performance data access and extraction

Since Codinhoto et al. (2013) 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 (Khaja et al., 2016); 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 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. E.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 (Solihin et al., 2015), the alternative was created to avoid these errors and specify exact data to be included in output of a lightweight and platform agnostic format.
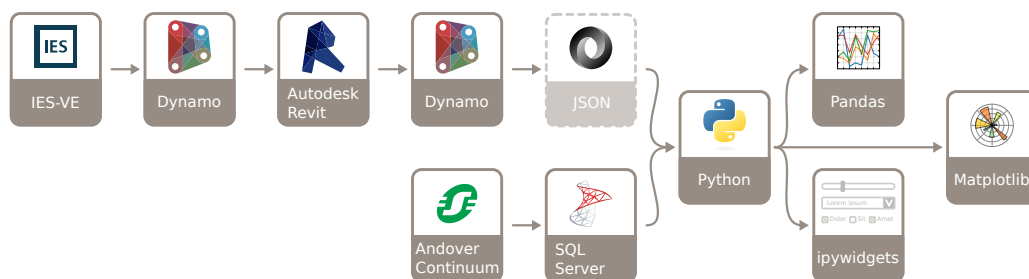

Figure E.2: Data transfer, extraction and visualisation process

E.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's systems, and its performance. The BMS implemented in the case-study building utilised a 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 (CIBSE, 2009). This form of monitoring enables the in-situ BMS to control Heating, Ventilation and Air-Conditioning (HVAC) equipment and identify faults (Piette et al., 2001).

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. (2015) 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.

Performance monitoring and querying

Numerous issues were identified in the commissioning and operation of the on-site BMS, 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 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 (van der Veen et al., 2012); 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.

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. E.3);
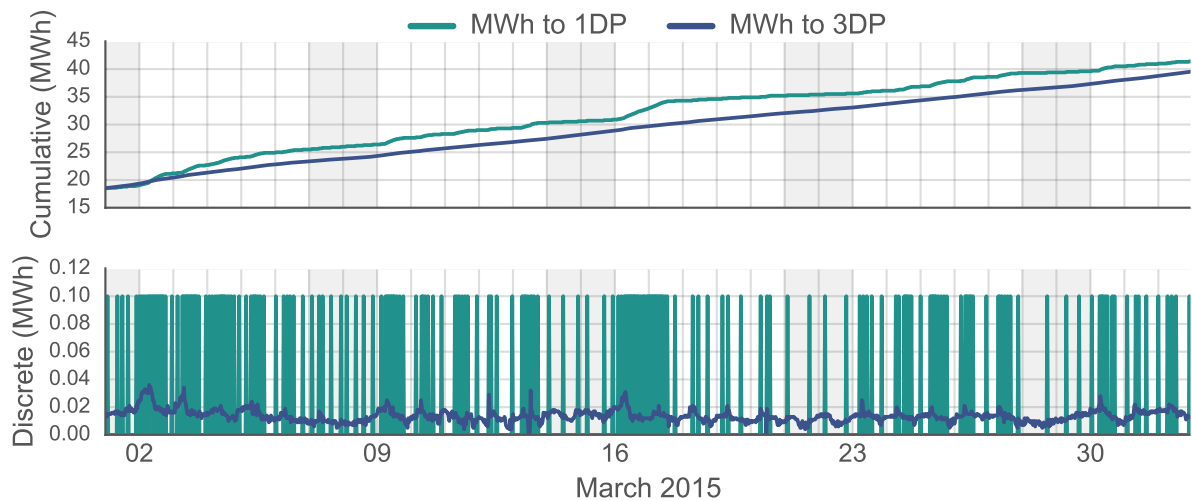
Figure E.3: Data resolution and granularity impact on record accuracy (measured at half hour intervals)

- 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 (Wright and Brown, 2008) or malfunctioning sensors. Outlier identification and removal from the data used the winsorized mean (Wilcox, 2010, pp. 150-157) of each record as a means of identifying and removing outliers.

E.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 Heirarchical 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 (McKinney and Reback, 2013). 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 (McKinney, 2010) 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 (Hunter, 2007). 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 (Pérez and Granger, 2007) to produce a user queryable environment in which performance could be monitored Fig. E.4a. Various data visualisation and analysis methods were developed using this link, including selection of monitored variable and time-span (Fig. E.4b) and historic summary to indicate historic trends (Fig. E.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. E.4d).

(a) Visual spatial performance

(b) 2D-histogram historic space/systems performance log

(c) Summary performance record

(d) Dashboard indicating deviation from predicted performance
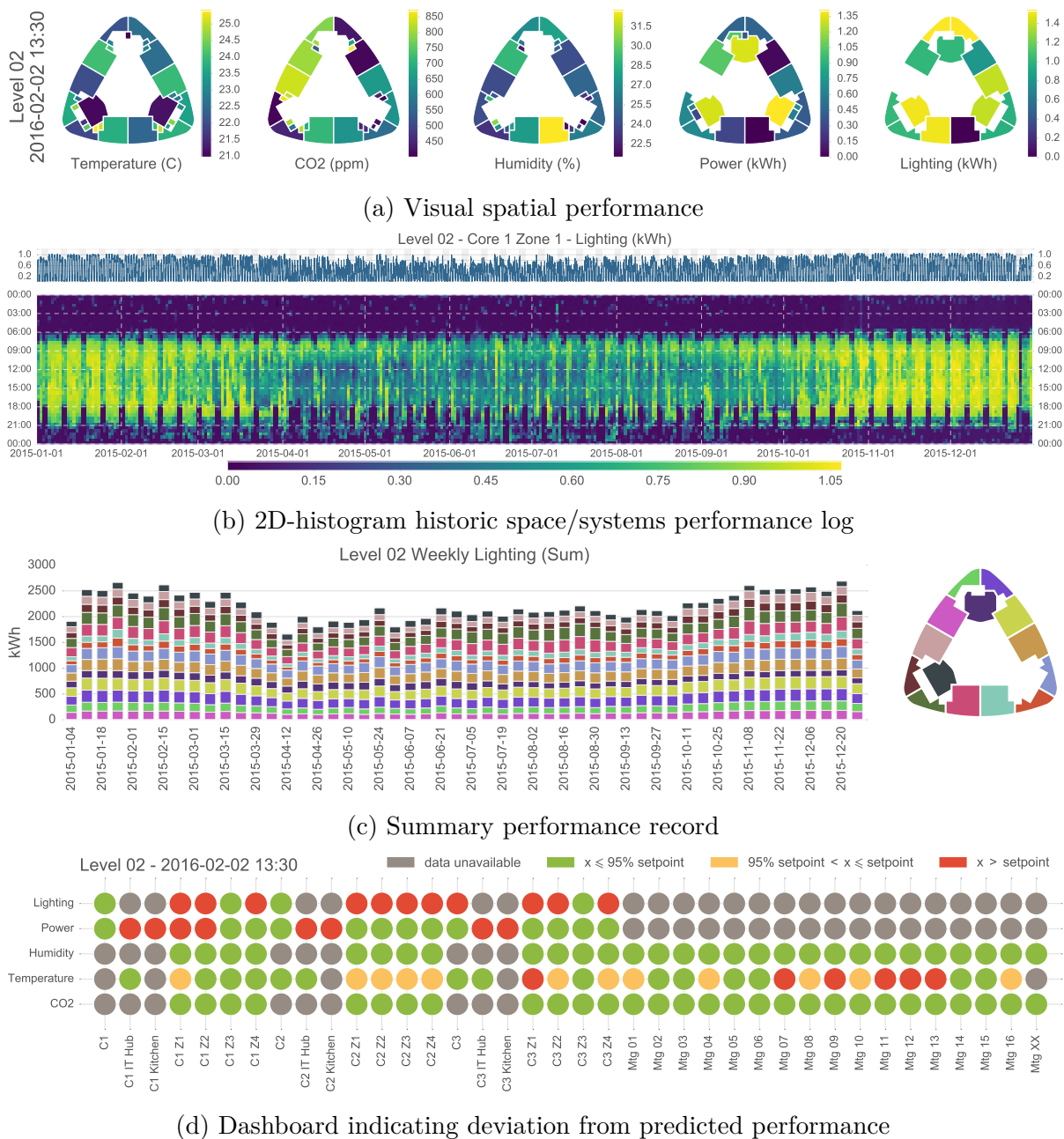
Figure E.4: Data visualisation from a BIM model and BMS records using Python Pandas and Matplotlib

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.

E.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.

E.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 (2009) and Barriball and While (1994) 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.

E.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 (2013) 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.

E.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.

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"*.

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 in the log book as the set-points 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 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"*.

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.

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 (Arayici et al., 2011), 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:

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 building's 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"*.

Skill

A combination of skills-based issues were noted, where the ability to correctly utilise a BIM model significantly impacted its 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"*.

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 made 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"*.

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.

– **ME:** *"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".*

E.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.

E.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.

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 (Cerovsek, 2011), with additional work required in interpreting it for FM purposes. Jylhä and Suvanto (2015) 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 building's 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 (Gerrish et al., 2015). 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.

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 (Codinhoto et al., 2013), 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.

E.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.

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 inter-

viewees 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.

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 set-point 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.

E.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 ineffectual.

Widespread application of BIM for purposes outside design development is unlikely to happen without corresponding and relatable 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 building's 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?

Acknowledgements

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F   Description of tools used

The tools used in the processing of information generated and monitored during the operation of the case-study building are briefly discussed here, providing context for the processes presented in Sections 4.4 to 4.7.

F.1   Python

The common language used throughout the tasks presented was Python (Python Software Foundation, 2016), chosen due to the availability of pre-existing libraries providing additional functionality, its simple syntax and the experience of the Research Engineer (RE). The additional packages used in this language included:

– Pandas* (McKinney, 2016b) – An open source library providing high-performance data structuring and analysis tools. This package was used extensively for interfacing with the historic Building Management System (BMS) through its Structured Query Language (SQL) querying capabilities. In particular, its functionality for processing time-series data provided numerous benefits in the interpretation of large datasets and error handling within these (Section 4.6);

– Matplotlib† (Hunter, 2007) – A 2-dimensional geometry (2D)-plotting library for visualising data (partially integrated into the Pandas package for quick dataset visualisation). All included charts were created using this package;

– iPython‡ (Pérez and Granger, 2007) – A rapid script development platform in which interactive data visualisations could be displayed without requiring compilation; and

– iPywidgets§ – This package was used to provide user-interactive functionality to the charting, data visualisation and exploration capabilities of Matplotlib within an iPython environment (Fig. F.1).

F.2   Monitored performance information

The tools developed in Section 4.7 demonstrating the potential for more effective management of information describing building energy performance, provide an interface to information commonly collected by a BMS. The issues encountered in Section 4.6 may

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*http://pandas.pydata.org/

†http://matplotlib.org/

‡https://ipython.org/

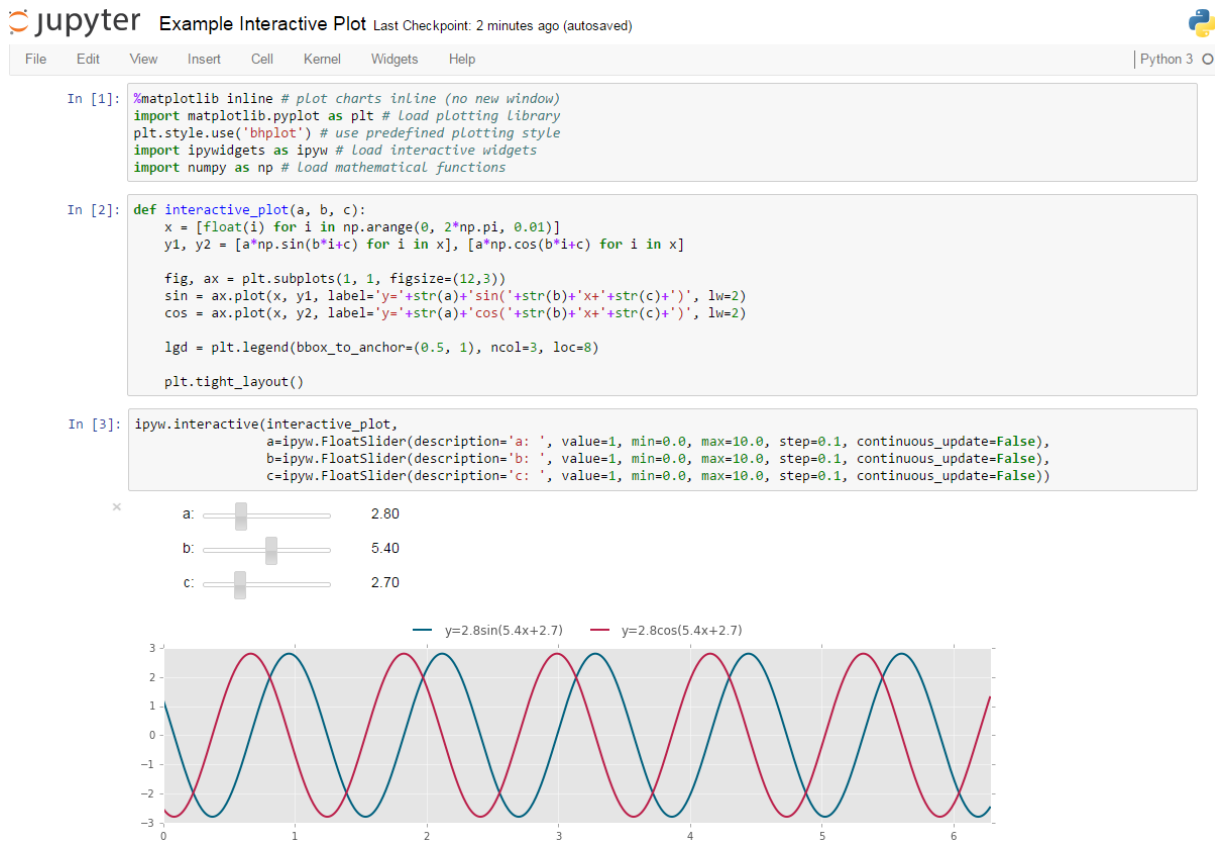§https://github.com/ipython/ipywidgets

Figure F.1: Interactive iPython environment

be managed using careful commissioning of monitoring and control systems to reduce error inclusion; however, the post-processing of this information for its attribution to Building Information Modelling (BIM) objects requires strict information similar to that defined in BSI (2007b).

Existing standards for building control and communication within buildings and across BMS's include protocols defining the method by which information is collected, transmitted and interpreted. These standards, such as BACnet (Newman, 2015), KNX (KNX Association, 2016), LonTalk (Echelon Corporation, 2009) and Modbus (Modbus Organization, Inc, 2016) do not specify the format in which historic building performance should be stored, but provide a common method with which controls and performance can be recorded in a common environment.

More recently, additional protocols for the organisation of information have been proposed to enable integration with BIM datasets and provide a common standard for equipment performance information classification. Project Haystack (Project Haystack, 2016) aims to standardise semantic data models to make information captured during operation available via web services for more open access of performance information. The Open Building Information Xchange (oBIX) (OASIS, 2016) similarly aims to open up access to information created by and describing building equipment via the web. Both address the movement from a single BMS network towards a larger decentralised network of multiple building datasets accessible via the web. Each proposes a less conventional method of storing such information, using alternative database structures for the collation of these large datasets to support their update and querying.

F.2.1 Methods of storing time-series performance information

Storage of information describing historic and live building performance data (including information not directly related to energy consumption, such as air quality) is normally achieved through collection of information in a common server-based environment. Within these, the collation of large datasets can be achieved, but correct commissioning is required for their effective utility (Gerrish et al., 2016b; Gerrish et al., 2015). The most common method for data storage through a BMS is in an SQL server. More recent protocols (Project Haystack and oBIX) for information storage and access are adopting more scalable, document-oriented structures with a simple mechanism to exchange data over web services.

Including time-series performance information in flat files (for example, Industry Foundation Class (IFC) and Green Building Extensible Mark-up Language (gbXML)) incurs a penalty in portability and accessibility, requiring larger files, and the capability of software to partially load these to access relevant information without loading the entire file into memory. Database methods reduce this requirement, instead requiring a dedicated computer for hosting and providing access to queried information upon request.

F.3 Summary

The choice of methods for the development of a prototype method for linking BIM and BMS environments was made due to the unique challenges inherent in the access, processing and interpretation of the information collected from the case-study building. No two buildings would demonstrate the same challenges, or issues in the information collected describing their performance. However, the tools and processes demonstrated (Sections 4.6 and 4.7) can be used to overcome many of the deficiencies in the handling data describing building energy performance efficiently.

Developments in the classification of information and structuring of data collected describing building performance will reduce the need for bespoke methods of data interpretation applied to each building. But until such a time as information can be accessed and interpreted without pre-processing to remove errors, human intervention for the restructuring and correction of data will be required.

G   Supporting data

The methods of collecting information through semi-structured interviews and surveys used during research are detailed here, indicating the questions posed to interviewees and respondents and their thematic categorisation and processing to output definitive conclusions.

G.1   Discipline BIM capabilities: Interview structure and thematic categorisations

In Task 2 (Section 4.2), a review of the research sponsors Building Information Modelling (BIM) capability was undertaken, using semi-structured interviews with representatives of distinct disciplines throughout the practice to determine its adoption and utilisation in the organisation currently. The following questions were asked in each interview; however, their order and inclusion varied depending on the flow of the conversation and interviewees responses.

As a semi-structured interview, the questions below were used as starting points from which discussion could be made around the subject matter. Many interviews were non-linear, resulting in questions being asked out of order and discussion moving into adjacent yet related topics. Therefore, response categorisation was used to distinguish relevance to broad topics of 'collaboration between stakeholders', 'information exchange', 'file standards and interoperability', future capabilities' and 'application specifically to building services and energy performance design'. Additionally, a general area of 'primary themes' where less topic specific comments could be collected was included for responses which could not be categorised as such.

– What is your position in the [research sponsor BIM implementation team]?
– Describe your current understanding of BIM – what it is and what does it mean to your role in particular?
– What are [the research sponsor's] current BIM capabilities?
– How well is BIM being implemented in your discipline currently?
– How does the disciple you represent compare with others in the practice?
– What lessons could be learnt from other disciplines in the practice?
– How do you work with external stakeholders outside the organisation (and within)?
– How are the processes being undertaken changing as a result of BIM implementation

currently?

– What are the main challenges to overcome before it can be used effectively?

G.2 Organisation-wide BIM perception survey

Following the initial review of discipline BIM capabilities in Task 2 (Section 4.2), a wider organisation-wide effort to improve BIM adoption and create a strategy for its wider implementation across projects and processes was undertaken by the research sponsor. Feeding into this, a survey of employees was used to determine their perception of organisation and personal BIM capabilities. The survey was administered using the research sponsor's Sharepoint intranet platform. The statements for respondent agreement are given below, with the majority of these quantified using a 5-point (Strongly Disagree – Strongly Agree) Likert scale (1932) for response analysis following collection.

Categorisation questions

- **In which region are you located?**
    - Americas/Asia-Pacific and India/Bath/Central Europe/London/Middle East/Northern Europe
- **Which discipline or team do you work in?**
    - Building services/Business development/Cities/IT/Other/Site/SMART/Structures/-Support
- **What is your position?**
    - Associate/Associate director/Engineer/Graduate/Other/Partner/Senior engineer/Senior technician/Technician
- **How much experience do you have working with BIM?**
    - None/≤1 year/1 to 3 years/≥3 years

Response agreement statements

- **Business need**
    - I understand the reasons why BuroHappold is adopting BIM
    - We must adopt BIM if we are to succeed in the future
    - If we don't adopt BIM now, I believe BuroHappold performance will decline
    - We will not remain viable as a practice if we do not adopt BIM
- **Business vision**
    - I understand the vision our leadership has defined for BIM adoption
    - Our plans for adopting BIM cover all the important issues
    - I am convinced that the vision for BuroHappold is the right one
    - It is clear to me how we will have to use BIM in the future
- **Business capability**
    - We have the right resources to make the adoption happen
    - Our leadership is committed to making BIM adoption happen successfully

– Our track record in implementing changes makes me confident that we will succeed

– Our key people work together effectively as a team

– **Business plan**

  – I know the overall plan for adopting BIM at BuroHappold

  – We are capable of delivering the required changes in the required time-scales

  – I believe our plans for adopting BIM are compatible with BuroHappold's goals

  – We are pursuing a coherent set of initiatives to adopt BIM

– **Leadership and guidance**

  – I believe our leadership can be trusted to make the right decisions on BIM

  – We have a clear vision of how we will work in the future

  – I believe I will receive the coaching and guidance I need

  – I believe the people guiding me through BIM adoption will know what they are doing

– **Personal desire**

  – I feel I need to adopt BIM to achieve my objectives

  – Personally, I cannot wait to adopt BIM fully

  – I feel excited by the prospect of adopting BIM

  – I want to change my current role and way of working

– **Personal values fit**

  – Adopting BIM will make my work consistent with my personal values

  – I will benefit from the BIM adoption that our business is undertaking

  – I will enjoy working here after BIM adoption has fully taken place

  – I will fit in well here after the BIM adoption has fully happened

– **Personal path**

  – I know how my role and style of working will change due to BIM adoption

  – I know what knowledge and skills I will need to acquire

  – I know what to do in order to achieve the changes required of me

  – I have a clear understanding of my next steps in the process of BIM adoption

– **Personal confidence**

  – I am fully confident that I can meet the challenges ahead

  – I feel certain that I will adapt to using BIM successfully

  – I have the right mix of skills to be a success in the new BIM world

  – I feel sure I can be successful in my work during the period of change

– **Involvement and participation**

  – I feel involved in the process of adopting BIM

  – My opinions on how we should adopt BIM are taken into account

  – My bosses understand how I feel about BIM adoption

  – I believe that I will be involved in decisions that affect me

G.3 BIM potential in building operation: Interview structure and thematic categorisation

In Task 8 (Section 4.8), the building designer and operators response to the developed prototype methodology for linking BIM and operational monitored building performance information was reviewed. This used semi-structured interviews following demonstration of the prototype to aid discussion around the topics of BIM adoption and implementation for the purpose of building energy performance management

The questions below were used as starting points from which discussion could be made around the subject matter. Many interviews were non-linear, resulting in questions being asked out of order and discussion moving into adjacent yet related topics. Similar to the semi-structured interview undertaken as part of Task 2 (Section 4.2), responses were categorised into themes of 'challenges in implementation', 'drivers for implementation', 'potential benefits', 'provision of supporting information' and 'use of supporting information'.

- How is building performance information given to the building operator?
- How is that information being utilised?
- What drivers are influencing how performance optimisation is being applied?
- What commissioning activities are undertaken to meet expected performance?
- What challenges have arisen as a result of this process?
- How do operators interface with the current Building Management System (BMS)?
- Are BIM-based technologies implemented in the operating method?
- Describe an ideal building performance management process
- What barriers must be overcome to enable that process?