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Using BIM capabilities to improve existing building energy modelling practices

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Abstract

Purpose – The purpose of this paper is to present 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 buildings energy performance in relation to its architectural objectives are given, with indication of the level of development 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 offers the capability to include BEM parameter-integrated construction information. The extent of information required for accurate BEM at stages of a building's design is key to understanding how best to record 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. 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 Design and development, Stakeholders, Information exchange, Building energy modelling, Building information modelling, Level of development

Paper type Research paper

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 project's 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 (Bordass *et al.*, 2004; Menezes *et al.*, 2012). 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.

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 (Figure 1).

Sacks *et al.* (2005) suggest error reduction could reduce whole project cost by 2.3-4.2 per cent, 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 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 buildings 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.

2.1 Interoperability between BIM and BEM

Several studies have attempted to incorporate information storage (BIM) and performance analysis (BEM) functionality (Table I), 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.

2.1.1 BEM. 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 specific services). Discretisation of design aspects (e.g. simplification of external climate or factors applied to fixed equipment performance values to account for changes in utilisation
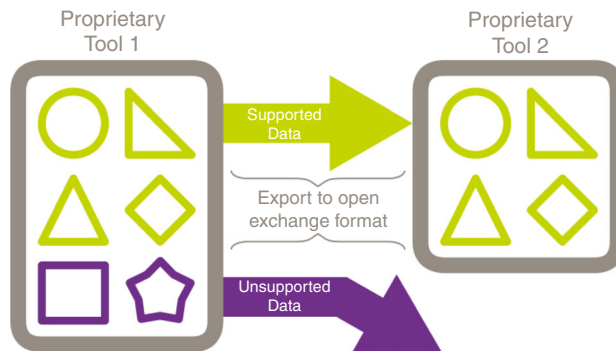

Figure 1.
Loss of data integrity/ accuracy through export via open exchange formats

Author/s	Technical barriers
Leicht and Messner (2007)	User error
	Information extent not defined
	Work duplication in transition between traditional and BIM systems
Azhar *et al.* (2009)	Value/cost prioritised 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

Table I.
BIM-integrated energy
assessment/design
studies

over time) are required to simulation 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.

2.1.2 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 (Azhar *et al.*, 2009; Bazjanac, 2008; Hitchcock and Wong, 2011), 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.

2.1.3 Interoperability. Information sharing between BIM authoring tools and BEM tools currently relies on open exchange formats of IFC and 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. Figure 2 demonstrates this through creation and transfer of information between Autodesk Revit and IES-VE via the gbXML and IFC formats.

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.

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 above reasons 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.

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, 2011) 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 buildings form, systems and operation changes based on the extent to which BEM takes place. For example,
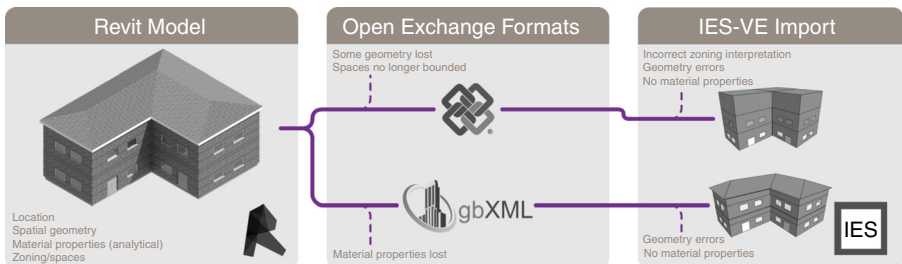

Figure 2.
Data loss from file creation and interpretation

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 II 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, Figure 2).

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 influence 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 Figure 3, with the information provided and demanded by each to assist identification of the basic information to be stored and shared via BIM.

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 (LOD) definitions provided by the American Institute of Architects and Associated General Contractors of America (2013) and data drop concept adopted by the UK 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.

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.

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)

Table II.
Basic information typologies supporting BEM and simulation

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Figure 3.
Energy performance
modelling stakeholder
information exchange
and development
process
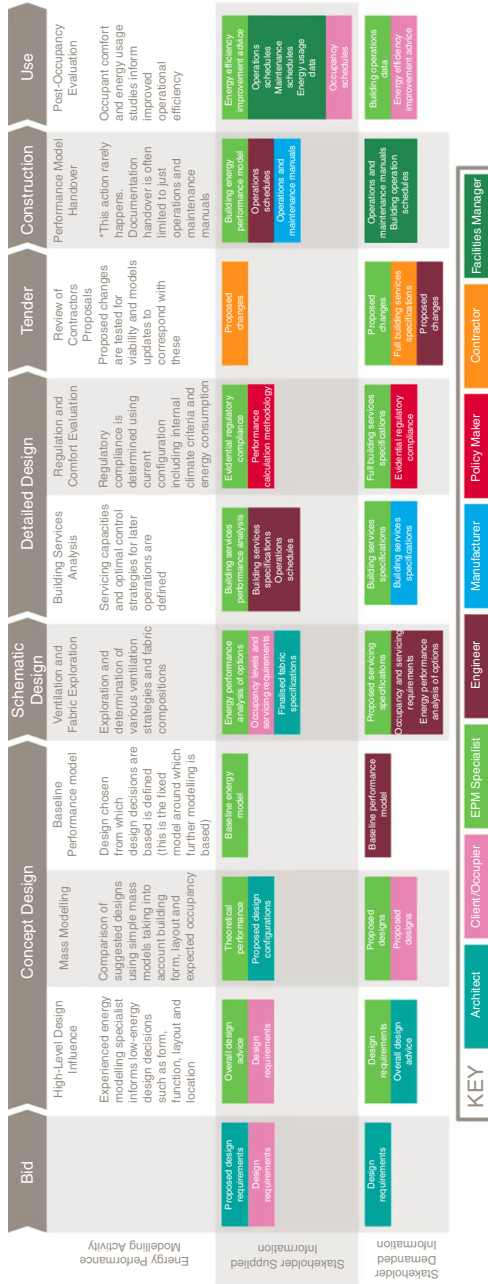
The means through which information in these projects is created, stored, shared and utilised is followed, noting key issues encountered, and potential improvements to procedures. The issues encountered are characterised as system-, skill- and process-based, and are discussed to contribute knowledge of factors limiting the integration of BIM and BEM in industry adoption of BIM.

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 (categorised as (skill) (System) or (Process)) are linked to points for discussion in the "Discussion" section of this paper.

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 BuildingSMARTs Information Delivery Manual for Building Energy Analysis (Welle and See, 2011) 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 (2012) 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 Figure 3.

Using existing design progression frameworks, including the activities currently being undertaken in the building design processes evaluated here, Figure 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.

Energy modelling can occur at any time during a buildings' 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 does not 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.

4.2 Information development
Quantising 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

UK 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, BSI (2007) specifies metadata 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 LOD concept. Detailed descriptions of this are given by the AIA and AGC (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 (with the exception of 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 III. As this develops throughout design, information becomes less likely to change and is therefore more representative of the completed building.

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

Table III.
Level of development for BEM parameters during building design

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 each stage (Process).

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 buildings 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 Figure 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, 2016) 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.
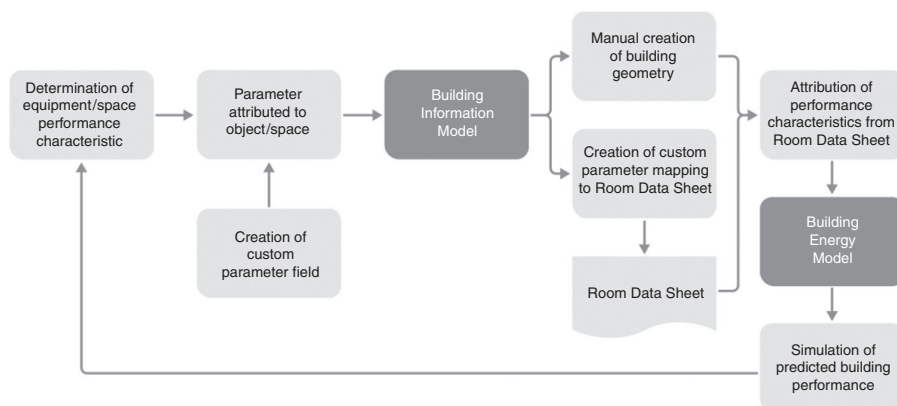

Figure 4.
BIM/BEM information
exchange process
without open
exchange formats

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 (Hitchcock and Wong, 2011; Sanguinetti *et al.*, 2012) (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 re-use in this area. These parameters are outlined in Table III and represent the range of data to be input into the BIM at each LOD before the next stage in design can occur; resulting in a comprehensive model describing a buildings 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. Figure 5 denotes this process, which will be tested in the development of a real project designing a university lecture space and laboratory building.
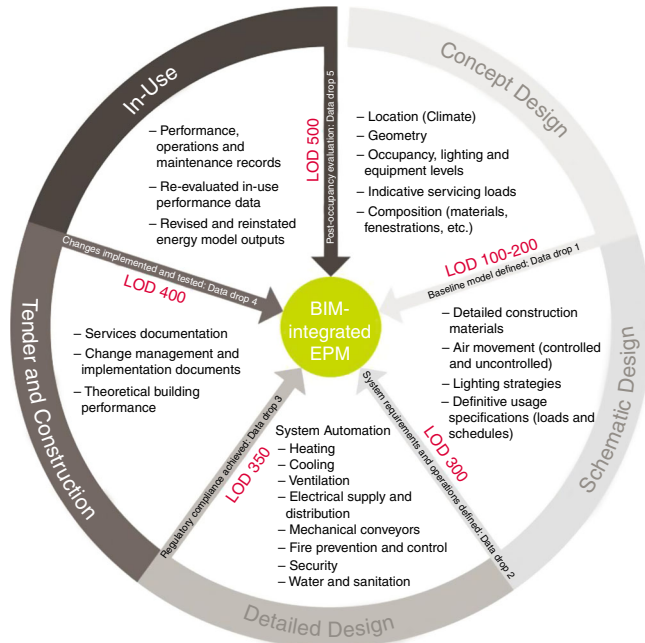

Figure 5.
High-level process map showing decision gates and stages for information extents assessment

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 Figure 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 RDS (as defined in LOD 300 Table III) 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 metadata attached to materials in the BIM. As previous attempts of exchanging data between the BIM and BEM using open exchange formats had failed (Figure 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 (Figure 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).

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.

5.1 Systems-based issues

5.1.1 Dis-integrated 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 (Bazjanac, 2008; Hitchcock and Wong, 2011; Kim *et al.*, 2012; 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 are required to facilitate both the development and adoption of these tools.

5.1.2 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 (e.g. the key performance descriptors of a piece of mechanical equipment). Attribution of parameters to objects in a BIM enables 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.

5.1.3 Information access. Post-construction, the information generated during design must be accessible to provide a rich source of O&M 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 buildings life-cycle.

5.2 Skills-based issues

5.2.1 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) (inaccurate space bounding), and most of these were present as a result of human error.

5.2.2 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.

5.3 Process-based issues

5.3.1 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 feedback into later designs to avoid future issues.

5.3.2 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 interpretation of data in an accurate manner. 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).

5.3.3 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 (Department of Energy and Climate Change, 2015).

6. Conclusions

In this study we presented a 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 buildings 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 buildings design progresses. The framework outlined here evaluated how information pertaining to the evolution of a buildings 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 metadata usable in later versions of that model.

- 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 buildings 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 buildings performance in both design and use can use these findings to focus work in the areas requiring most development.

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