

Title:

A framework for the utilization of BMS data in BIM to bridge gaps between building design and operation

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Abstract

Research on digitizing the various aspects of a typical building project has been on the increase since the advent of Building Information Modelling (BIM). Most efforts build on information technology capabilities already achieved in the various professional domains associated with different stages of the building life cycle. It is predicted that BIM will help to drastically reduce errors, fast-track project delivery time and save implementation costs. As such BIM is now being utilized in the various professional domains and project stages. However, research suggests that the building operation and management stage is being left behind despite the abundance of data collected using building management systems (BMS) of varying degrees of sophistication. It is therefore important to consider exploring BIM applications that encompasses the building operation phase. This will enhance the evaluation of building performance in use and provide feedback to the design stage which could help eliminate design-related performance issues. A framework for utilizing feedback loops from building energy consumption to inform and improve design and facility management in a BIM environment is therefore proposed. A prototype illustrating the framework is implemented in .NET framework interfaced with a BIM-enabled tool and tested in the refinement of a pre-designed school using data from the operations phase of another school delivered previously. We conclude that the framework developed in this research can contribute to bridging existing gaps between the design, construction and operation phases of a building's life-cycle.

Keywords: BIM; Building performance, Data acquisition, Facilities management

1 Introduction

The advent of BIM promises to greatly reduce the seeming complexities inherent in the facilities manager's tasks as well as those of other professionals in the construction sector. Current research on building information modelling (BIM) focuses on digitizing the various aspects of a typical building project as part of the design and perhaps construction stages. Hence, research efforts towards addressing BIM use in the operational phase is still at its infancy [1, 2].

Most of the current research efforts are built on the BIM/computer-aided capabilities already achieved in the various professional domains associated with the different stages of the building life-cycle such as planning, design, construction and, perhaps operations. For example, the object-based features and parametric modelling capabilities displayed by contemporary BIM-enabled systems are improvements on CAD systems and the earlier achievements made in the graphical representation of solid geometry [3, 4]. Similarly, domain-specific tools (e.g. for structural analysis and design, architectural drafting) have been in use and improved over the years as advances were made in information technology and communication. Perhaps this approach to software development resulted in persistent issues with interoperability, and thus barriers to seamless information exchange. The overall aim of the developing contemporary BIM approach is to provide consistent digital information that can be reused by stakeholders throughout the building life-cycle [4, 5]. It is predicted that BIM will help to drastically reduce errors, fast-track project delivery time and save implementation costs, as well as assisting with asset management.

As the scope of BIM gradually expands towards asset management, there is the need to learn from building performance by establishing and utilising feedback loops to the appropriate stages in the project life-cycle. This can be achieved through the establishment of frameworks such as the one implemented in this research. The envisaged benefits of using BIM for asset management include providing instantaneous results on anticipated building performance and identifying areas (such as energy modelling and sustainable material selection) of weaknesses in design and specifications so that they can be improved in forthcoming projects. Although sustainability (including energy) analysis tools for early planning and design purposes exist, the performance data they generate are disconnected and separate from their ultimate downstream use by facility management systems [6]. This also means that there is a gap in the upstream flow of feedback from the building's operational phase. The general consensus from literature [1, 6] is that the building

operations phase is disconnected from the earlier phases of the project life cycle in terms of delivering the product and information exchange. It is alleged as a tradition but also as a key obstacle against asset owners extracting maximum value from their investments [6]. Thus, the anticipated value of design-operation integration can only be fully accrued if feedback loops from the building operations phase can be established.

In order to meet the relevant standards, design specifications usually identify materials and systems for production/construction according to anticipated performance mainly based on laboratory tests and manufacturers' claims on performance. The Literature suggest that the design stage offers a good opportunity to influence cost and sustainability [7, 8]. It is therefore important that performance information is verified from actual historical performance data collected during the operations phase. However, professional domains have not sufficiently explored this opportunity as identified in Oti and Tizani [9] and Wang et al [10]. Alwan et al [6] remarked that assets have been often made attractive by declarations of design aspirations while an ever expanding performance gap exists. In facilities management (FM), existing information gaps with design are partly because of the way projects are being delivered with little or no consideration for the integration of FM issues unless a Client consciously requires this to be done [6].

This paper aims to devise a framework for such integration. It illustrates how feedback loops from operations to design can be established by incorporating building management system (BMS) data into a federated BIM to inform the designer and the facility manager. Its objectives are to: (i) ascertain challenges in the integration of building operation and BIM (section 2), (ii) identify building energy consumption data acquisition and feedback options to BIM (Section 2.2), (iii) establish a framework for BMS data utilization in BIM (Section 4), (iv) implement a prototype to link BMS data to BIM (Section 5.1) and (v) test the system implementation in a real-life project (Section 5.2).

The paper is divided into seven sections. An introduction and insight into the research problem is given in Section 1. Section 2 provides a background on the role of performance data acquisition in facility management with respect to BIM leading to the description of the adopted research methods in Section 3. Sections 4 and 5 respectively present the proposed implementation framework for BMS data utilization and integration in BIM and illustrate a test case using the developed prototype. Section 6 discusses the research limitations including likely areas of future expansion and Section 7 concludes the paper.

2 Operations Data acquisition and integration in BIM

There are potential areas for BIM application in facilities management where feedback can be useful. Some areas already identified by Becerik-Gerber et al [1] include locating building components, facilitating real-time performance data access, visualization and marketing, considering ease of maintenance, creating and updating digital assets, space management, planning and feasibility studies for noncapital construction, emergency management, controlling and monitoring energy consumption, and personnel training and development.

While the modalities of BIM implementation may differ in all these areas, what will perhaps be common to all is the process of harnessing feedback from the model to inform and improve asset performance and vice versa. This process will require more than just engaging the facility manager in the design stage as suggested in Wang et al [10]. It will require careful planning, mapping and integration of the facility management operations into the BIM approach. This paper stems from this premise and evaluates the option of integrating building management system (BMS) into a federated BIM.

The use of building energy consumption data collected using BMS to improve the design and operation of buildings is an active area of research. It is concerned with the active control of energy-dependent systems in the operation phase of the building [11]. The technological advances in BIM offer opportunities to integrate BMS data. This area needs to be fully explored. The existing gaps in linking BMS data to BIM has been noted for contributing to the inconsistencies in graphical energy data generated from manual input of repetitive energy management system data [1].

The technological advances made in the development of building energy performance data acquisition systems are well acknowledged [1, 12, 13]. However, there have been challenges in utilizing such data to meaningfully inform and improve subsequent project design and delivery. The Big Data syndrome is also associated with the streaming of energy performance data from such acquisition systems [14]. More often than not, energy performance data collected from acquisition systems grow very large in size and is too unstructured to put to immediate beneficial use without some form of structuring and analysis.

2.1 Potential areas and tools for data acquisition during operations phase

Large amounts of data and information are produced at each stage of a building project. Detailed design information is produced for the successful delivery of the built asset and its end-use. Data is also generated during the life-time of the building until it reaches the end of its life. Most data that is generated in this latter stage is energy consumption data. Data may also be gathered on the maintenance activities and on occupancy levels. The energy performance of a building has an important impact on its overall performance. Literature suggests that the incorporation of energy efficient measures in buildings could improve the economic value of buildings [15-17]. Thus, clients and tenants prefer properties that will cost less to operate and maintain. Integration of BMS **data into BIM may assist in this if a framework which helps make sense** of abundant BMS data on energy consumption to reduce consumption levels can be developed. One of the current problems associated with this integration is that BMS data reveals how much energy is being consumed but it cannot **on its own determine why this much energy is being consumed.** Yu et al., [18] summarises factors influencing total energy consumption of a building into 5 main categories: (i) Climate, (ii) Building-related characteristics (type, area, orientation etc.), (iii) Building services systems and operation (space cooling/heating, hot water etc.) (iv) User-related Characteristics (user presence/occupancy) and (v) Building occupants' behaviour which is a function of social and economic status as well as preferences for indoor environmental quality. The first four factors can be modelled into building energy simulation programmes with certain limitations especially with respect to occupancy. BMS can be used to collate energy data on operational performance to a large extent. However, it has been difficult to accurately capture data on occupants' behaviour in terms of its influence on energy consumption, and more importantly to automate the collection of such data. Thus to make better sense of inherent energy consumption levels in BIM applications, it will be useful to integrate the modelling of these five factors that influence energy consumption. However, this is difficult to achieve for two obvious reasons: 1) it is difficult and costly to automate data collection in certain areas, e.g. in occupancy; and 2) very rich and detailed data on occupants' behaviour, which is variable, is required to make sense of energy **consumption levels. This research focuses** on developing a framework that would enable the authors make sense of (iii) Building services systems and operation as a starting point.

Building energy consumption modelling tools that could be associated with the aim of this paper relate to design and facility management (Table 1). Most of the design tools utilize conceptual design information such as volumetric and spatial data which could be provided

directly through modelling or imported using gbXML file formats. These tools have been found to be lacking **in providing requisite** feedback of performance histories to BIM. Thus, it is difficult to input raw or refined BMS data in these tools for the purposes of analysis and linking such performance data back to a building information model for a number of reasons. First, a large volume of data will usually be involved [19-21]. Second, these tools cannot be easily reconfigured to receive energy performance data in a manner that suits the operations phase of individual buildings. Third, facility management tools do not carry out energy design and analysis at the early project phases but have the capability of capturing and reporting data generated at the field or during building operation. Fourth, these tools are largely dependent on the internet and cloud services.

Another option is to integrate BMS data to a building information model. Although literature on verified applications in this field is scarce, there have been speculations that Data Acquisition Technology (DAT) has been integrated with Onuma Planning Systems [13]. Also, there are indications that a building information model can be populated with energy consumption data using Autodesk Project Dasher [13]. Some demonstrations of Autodesk Project Dasher as a visualization tool overlaying energy performance data on 3D BIM can be found in Attar et al. [22] and Khan and Hornbæk [23]. Onuma Planning Systems and Autodesk Project Dasher are commercial and dependent on Cloud services. Therefore, licences are likely to be costly. Besides this challenge, these approaches may need to be realigned to address user targets concerning post-occupancy evaluation, and the reconfigurations that may be required could be costly and time-consuming. Also there could be challenges with familiarity and technical know-how on the part of building occupants/users. Thus, building owners who may not come from the design and construction background may struggle to understand what systems they need and their associated operation compared to a bespoke developed plug-in such as that proposed in this research.

Table 1: Building energy management tools

TOOL	FUNCTIONAL DESCRIPTION
<i>Building energy performance tools for design purposes</i>	
Autodesk Ecotect	Sustainable design analysis software that offers a range of simulation and building energy analysis functionality to improve performance of existing buildings and new building designs. Its capabilities include Whole-building energy analysis, Thermal performance, Water usage and cost evaluation, Solar radiation, Daylighting and Shadows and reflections
Autodesk Green building studio	Cloud-based energy-analysis software used for whole-building analysis optimization of energy consumption and carbon-neutral building designs in early project phases. Functions include Whole-building energy analysis, Detailed weather data, Energy Star and LEED support, Carbon emissions reporting, Daylighting, Water usage and costs, Natural ventilation potential
DOE-2	A building energy analysis program that can predict the energy use and cost for all types of buildings. DOE-2 uses a description of the building layout, constructions, operating schedules, conditioning systems (lighting, HVAC, etc.) and utility rates provided by the user, along with weather data, to perform an hourly simulation of the building and to estimate utility bills.
eQUEST	A building energy use analysis tool that allows comparison of building designs and technologies by applying sophisticated building energy use simulation techniques.
BEopt	The BEopt™ (Building Energy Optimization) software can be used to evaluate residential building designs and identify cost-optimal efficiency. It can be used to analyse both new construction and existing home retrofits. It provides detailed simulation-based analysis based on specific house characteristics, such as size, architecture, occupancy, vintage, location, and utility rates.
<i>Facility Management tools</i>	
Artra (Trimble)	Artra provides seamless information links between the multiple engineering systems. It enables information to be provided in the relevant format for jobs and has mobile capability for delivering complex data.
Onuma Planning Systems	A web-based Building Information Modelling (BIM) tool that can be used for early planning, Project Program Development, Charrettes (BIMStorms), Schematic Design, Connect to other BIM applications, Cost estimating, Energy Analysis, Life Cycle Costing, Facility Management, Portfolio and Program Management
Autodesk Project Dasher	Project Dasher is a web-based application that helps to augment existing Autodesk® Revit® design models with real-time building sub-meter and sensor data on electricity and occupancy. It presents a comprehensive framework for monitoring building performance using a visualization hub where collected data from various sources is intuitively aggregated and presented in 3D to enhance the ability to infer more complex causal relationship pertaining to building performance and overall operational requirements.

2.2 Approaches to the integration of BMS data to BIM

BIM tools are still developing. Currently, they have not been fully furnished with facilities for carrying out energy analysis of data directly from BMS. The purpose of this paper is

therefore to facilitate the understanding of how BMS data analysis can be used in BIM to aid building professionals/users. A pre-designed scheme, where buildings such as schools are built from an existing design with some modifications/variations should they become desirable or necessary, is used for illustration purposes. Such a scheme is chosen as it is considered to benefit most from feedback on the performance of the building during its use to successive design iterations. First, the most effective means to providing such feedback are identified. Then, a tool to extract and compare BMS data analysis is proposed to inform design iterations taking advantage of the recent technological developments in BIM and the increase in its uptake. The integration of facility management with BIM that particularly relates to the aim of this paper has two basic approaches to linking BMS data to BIM: (1) BMS – Energy Analysis Tool – BIM link and (2) Energy Consumption Viewer Plug-in – BIM link.

- **BMS – Energy Analysis Tool – BIM link**

In this approach (Figure 1), it is envisaged that BMS data can be sent to Energy Analysis tools (via file transfer, the internet or cloud services) to carry out requisite analysis before feeding the outputs to building models in a BIM-enabled tool. This approach can take advantage of database management systems, open file formats and common data environments. The linking of DAT to Onuma Planning Systems [13] falls into this approach. It is also possible to have the Energy Analysis Tool in a single module with the BIM tool (such as Autodesk Project Dasher) or integrated with the BMS data collection as presented in Attar et al [22] and Khan and Hornbæk [23]. These systems are economically demanding to acquire and require reconfiguration to become fit-for-purpose to address post-occupancy evaluation targets [13]. Although these tools may have some high level sophistication (having been developed by established commercial software developers), there are still challenges with flexibility in configuring them to stream data from existing BMS systems due to interoperability issues [19].

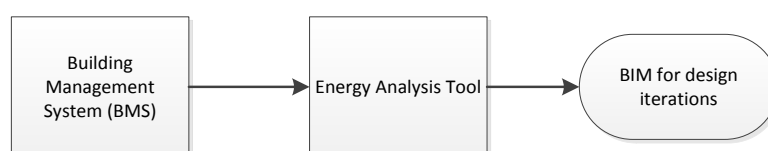


Figure 1: BIM - Energy Analysis Tool link

- **BIM – Energy Consumption Viewer Plug-in link**

Here, a BIM tool is bolted with an external application such as our proposed Energy Consumption Plug-in to enable the viewing of energy consumption profiles of buildings (Figure 2). A plug-in is an external application which can be continuously improved in sophistication through computer programming. The plug-in can use processed/refined BMS data and it can be linked to a BIM-enabled tool through associated application programming interface (API). Depending on the sophistication of the plug-in, aspects of consumption data analysis could also be carried out in the plug-in environment. The plug-in serves as a new external tool to the BIM environment which can be called up for the visual presentation of historical energy performance to ease understanding of non-experts such as building occupants. More importantly, it allows for the comparison of performance across a number of projects which have been built primarily to the same design. As a result, it becomes the initial step in determining the reasons behind different levels of performance in different buildings which would have had similar performance results during design simulations. This approach, thus, provides a flexible way to input refined BMS data into the prototype system for display in a BIM environment that can be used in refining the pre-designed schemes.

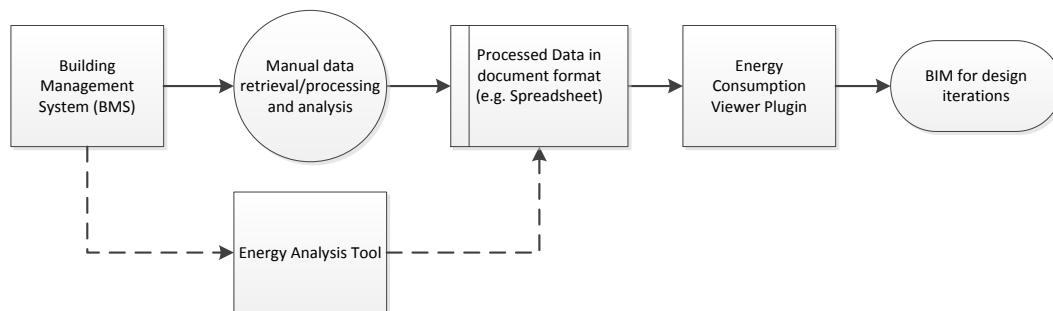


Figure 2: BIM - Energy Viewer Plugin link

3 Research method

One of the objectives of the research project is to achieve better integration of energy performance data from completed projects in a BIM environment. The research ideas about BMS-BIM integration are tested as part of the continuous improvement of a pre-designed scheme for schools, which is delivered as a turnkey project using a framework agreement. The pre-designed scheme is particularly important for this study as there is a clear advantage of using knowledge from the operations phase to continuously improve it and the associated federated model for successive clients. Also, facility managers may learn from historic performance records contained in the model to manage future consumption. In the

sub-sections, further description is given about the test project and energy performance data gathering process. The approach adopted in modelling sourced data and the prototype developments are also described briefly as well as the context of key terms featuring in the paper.

3.1 Test project description and data sources

A real life case is chosen to evaluate how BMS data can be analysed and feedback sent to **design iterations using BIM. The case** is a new primary school project based on a pre-designed scheme with good energy performance. The school building is a single storey steel portal frame structure with a floor area of 1187 m². It has an overall Energy Performance Certificate (EPC) 'A' rating suggesting that the building excels in (i) All-electrical services strategy, (ii) Solar-thermal hot water system and (iii) Natural ventilation via windows/roof lights, etc. The performance targets for the building were set in terms of energy use, running costs and carbon emission levels for both regulated usage (building services such as heating, hot water and lighting) and un-regulated usage (IT server, kitchen equipment, plug in appliances etc.), which formed an integral part of carbon emission targets at the time this project was conceived.

A literature review has been carried out to establish research gaps and appropriate methodologies for achieving the set objectives. The review covered aspects relating to the modelling of building energy consumption histories from building energy management systems (BMS) to BIM environments. This helped in identifying research gaps associated with incorporating building performance information to BIM and possible process options for such communication.

3.2 Modelling approach

For the aspect of information modelling, established techniques such as the Rapid Application Development (RAD) approach [24] aided by IDEF3 modelling language, was used to develop a framework for utilizing performance histories in BIM and facilities management. The RAD methodology employs cycles of re-specify, re-design and re-evaluate on the prototype system from its conception to when it achieves a high degree of fidelity and completeness. The prototyping process is therefore characterized by increased speed of development and experiences of series of births rather than deadlines. It informed the implementation of a prototype in .NET Frameworks which entailed the interfacing of a

BIM-enabled tool with object oriented representation of information in C# programming language.

Series of system testing typical to the RAD approach were carried out to refine the prototype and check that underlying programming algorithms and assumptions are functioning correctly. To achieve the overall testing of the prototype, case-illustration has been employed using consumption data already acquired from a building management system on a school **building project based on a pre-designed scheme. This** opportunity arose from the on-going research collaboration on low-impact school procurement which has developed within a mutually acceptable ethical understanding. In addition to achieving programming requirements such as flexibility and ease of operation, suggestions from project stakeholders including the main contractor, the architects, the project managers and the energy experts were injected into refining the framework.

3.3 Definition of key terms

In this research, we build the framework for BMS data utilization in BIM around the digitized building model which is a representation of the physical building (life-building) to be built or already built. Just like the life-building undergoes transformation from stage to stage, the digitized building model also changes but at a very different pace as conceptually illustrated by the authors in Figure 3. At the early stages of planning/design the digitized models develop, in terms of extractable information, at a much faster pace than the life-building and then lags at the latter stage. Thus, the realisation (construction) of the life-building is dependent on the digitized building model (As –planned BIM) which in turn becomes dependent (updated with information as As-built BIM) on the realised (constructed) life-building. During building retrofitting, the As-built BIM may be used for retrofitting design or be updated with the new retrofitted information when completed. At the end-of-life of the physical building, the digitized building model (As-built BIM) can further be updated finally and archived for future uses. For better understanding, the terms As-planned BIM and As-built BIM are defined in the context of this paper.

(i) As-planned BIM

We refer to As-planned BIM as the digitized building model containing design specification as provided by building professionals for the purpose of construction on site. It encompasses all BIM developments that precede the completion and handover phase. As-planned BIM may include the individual digitized models of various professionals or the federated model of the individual profession BIMs.

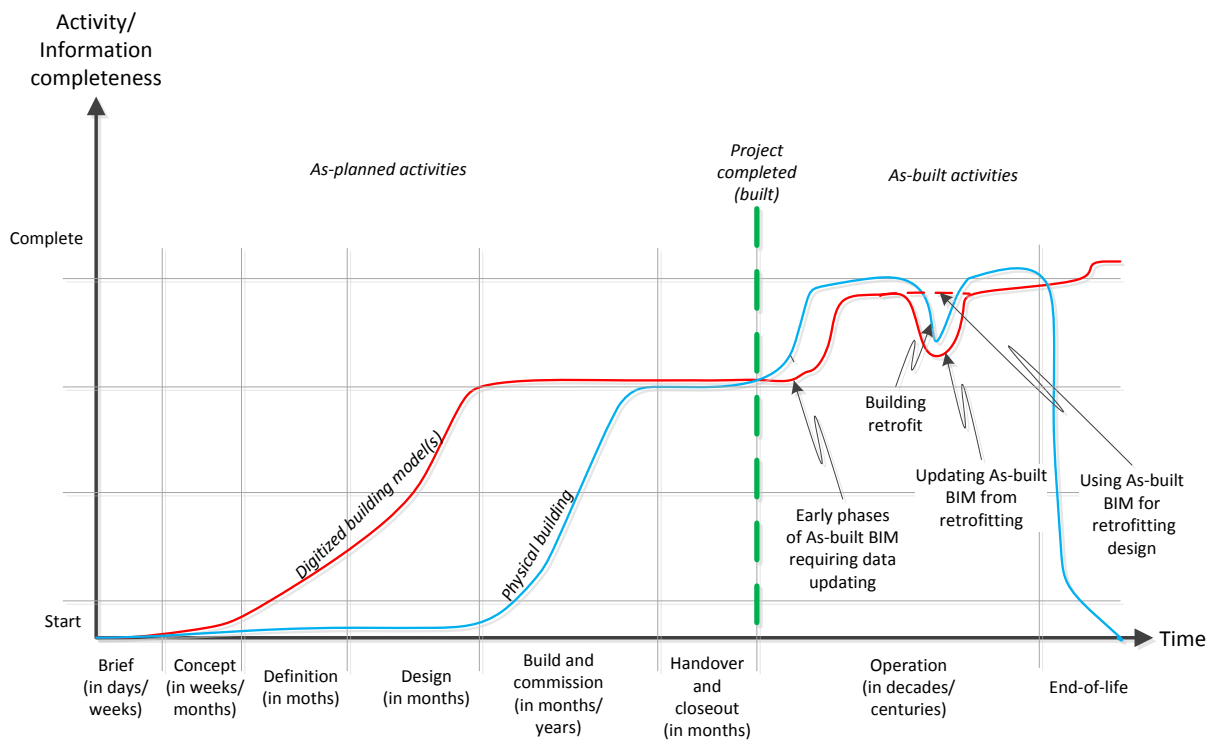


Figure 3: As-planned versus as-built information in building models

(ii) As-built BIM

The use of the term As-built BIM in this work is consistent with the literature which describes it to be the as-built or as-is representation of the constructed building at the state of survey [25]. As-built BIM may be developed from As-planned BIM, using progressive point cloud laser scanning, images from high resolution/density cameras etc. [26, 27]. Since it is a reflection of the building as-is (all elements – Architectural, structural, MEP etc. – in place), the federated model after the completion of construction is a good starting point for generating and updating the As-built BIM.

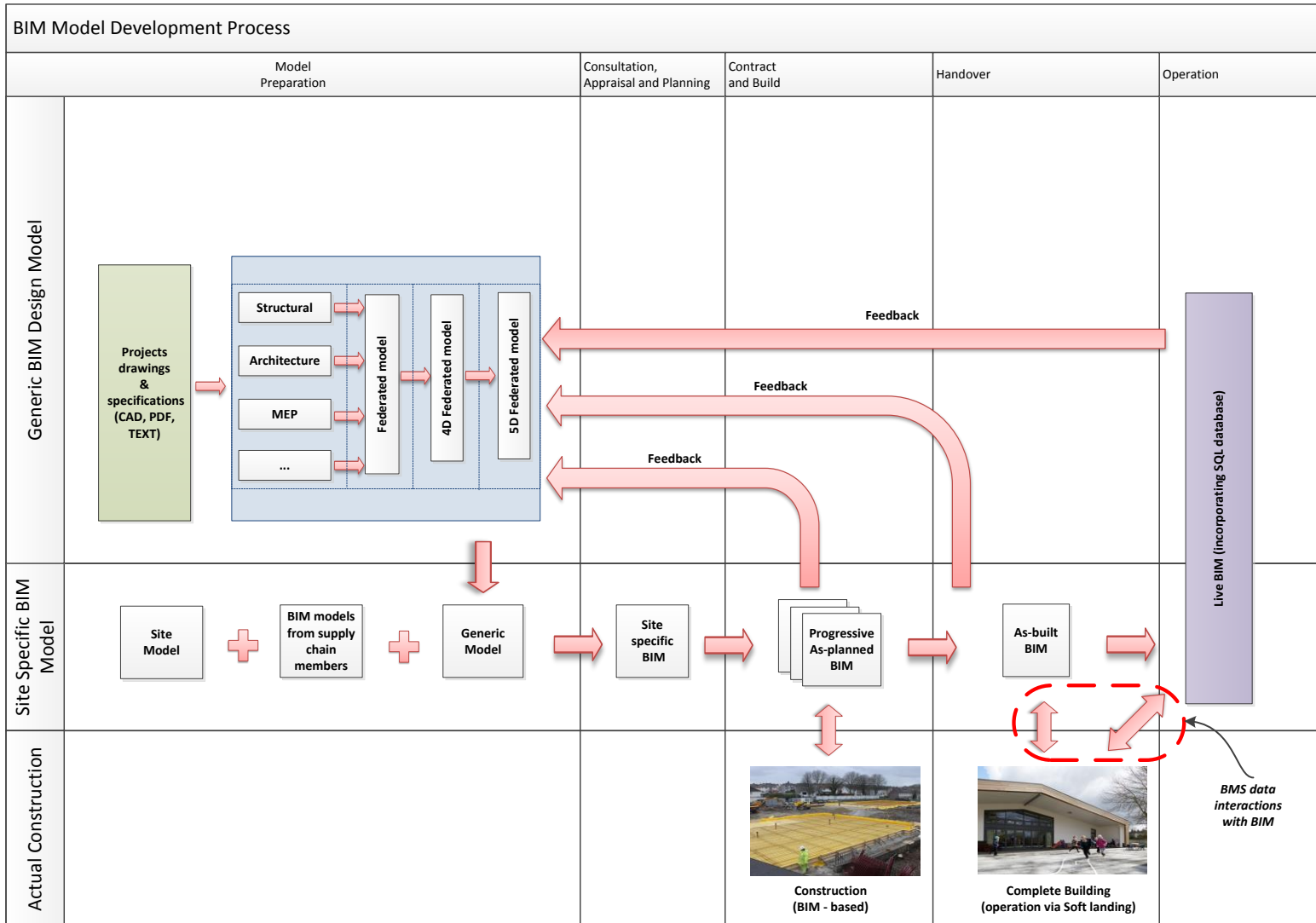
4 A proposed framework for data acquisition utilization in BIM

As the building in the case is a product of pre-designed scheme for schools, there are two levels of the digitized building model development in the BIM environment. First, there is a generic digitized building model level in which pre-designed models are continuously developed to strengthen the market offering. Second, there is the site-specific digitized building model level in which a pre-designed model is adopted to integrate it with other models (e.g. site and furniture) to form a site specific model. The development is illustrated in Figure 4. Upon confirmation of a project proposal, existing drawings, textual information

and specifications from a generic digitized model are reproduced and then integrated with various digitized site models and supply chain models. These combinations can then be further tailored as site- specific building information models for construction and operation. These processes produce progressive As-planned BIM, As-built BIM and the live BIM which are used for the actual construction phase and during operations. They also serve as channels to supply feedback to the Model Preparation stage for the refinement of the generic building design model. The aspects that are of direct concern with the discussions in this paper have been highlighted by the broken line in Figure 4.

An aspect of demonstrating a learning process through feedback is explored in the proposed framework for data acquisition utilization in BIM is illustrated in Figure 5 using IDEF3¹ notations. The framework is aimed at ensuring the utilization of BMS data to facilitate continuous improvements in building design and facility management by learning from historical records of energy usage. This is achieved through identifying and modelling factors that influence consumption levels associated with various categories of energy usage. The process is decomposed to two lower levels: (1) Data acquisition and analysis process (DECOMP 4.1) and (2) Analysis of causes and effects (DECOMP 12.1) from the top level (Improve BIM through data acquisition).

¹ IDEF3 is a structured descriptive process modelling language used to capture sequence of events and express knowledge about the operation of systems 28. R.J. Mayer, C.P. Menzel, M.K. Painter, P.S. Dewitte, T. Blinn, B. Perakath, Information integration for concurrent engineering (IICE) IDEF3 process description capture method report, 1995, DTIC Document.



1

2 Figure 4: Using BIM to improve the turnkey process

3 **4.1 Improve BIM through data acquisition**

4 The Top Level of the framework (Figure 5) expresses the overall aim of improving BIM
5 through data acquisition. It is comprised of 7 processes known as units of behaviour (UOBs),
6 two of which are parallel – implying alternative routes of utilizing acquired data. UOB 1 is
7 based on the assumption that a digitized building model, known as As-planned BIM, exists
8 for a proposed building project. The proposed building is constructed and operated based on
9 the As-planned BIM as indicated in UOBs 2 and 3. Feedback loops from UOBs 2 and 3 to
10 UOB 1 have been indicated to capture modifications of design models as a result of
11 interactions with construction/operation teams. It is at the operation stage, UOB 4, that
12 actual building performance data is acquired for further utilization to meet various intended
13 purposes. UOB 4 is expanded at the first decomposition level. However, the acquired data
14 from this process can either be used to benchmark and reduce energy consumption (UOB 5)
15 or utilized to improve design (UOB 6). These two processes converge to be integrated into
16 the digitized building model (BIM) for future use in UOB 7. This is particularly relevant for the
17 building information model in this case of the pre-designed building model for delivery. So,
18 the knowledge gained from the analysis will be used for the development of the pre-
19 designed building model and/or to learn from historical performance records contained in
20 models to manage future consumption. One challenge that is worth careful consideration
21 and perhaps further research is who will be responsible for feeding information back to the
22 model at the building operation stage and how this will be done. This issue is discussed
23 further in Section 6

24 **4.2 Data acquisition and analysis process**

25 In Figure 5, the highlight of data acquisition and analysis process (DECOMP 4.1) is the
26 comparison of As-planned and As-built performances (UOB 4.1.9) from the preceding
27 process of analysing the building performance (UOB 4.1.8). In UOB 4.1.8, data captured
28 from the BMS is processed into formats showing energy consumption patterns for easy
29 understanding and assimilation. This might require special skills peculiar to services
30 engineers, HVAC specialists or the post-occupancy evaluation team, perhaps using
31 purpose-built IT. For UOB 4.1.9, the comparison will yield two groups of information. The first
32 group, represented by UOB 4.1.10, is the path where the As-built performance is lower than
33 the As-planned performance. There could be a number of reasons resulting in this
34 phenomenon. In addition to design errors and possible construction deficiencies, one other
35 likely reason is that the facilities/systems may not yet have been occupied according to the
36 capacity for which they have been designed. The second group indicated in UOB 4.1.11

37 encompasses all As-built consumption levels that are greater than that of their
38 planned/designed counterparts. The focus of further analysis is on this group. It entails
39 determining reasons and causes of gap/discrepancies (UOB 4.1.12) resulting in As-built
40 consumption levels rising above design benchmarks. The outcomes of these two parallel
41 paths converge as information to be utilized by the Facility Management team for product
42 improvement purposes. In the overall process, the resulting feedback lessons flow to
43 planning and design for enhancing the process of delivery and the improvement of the
44 product itself.

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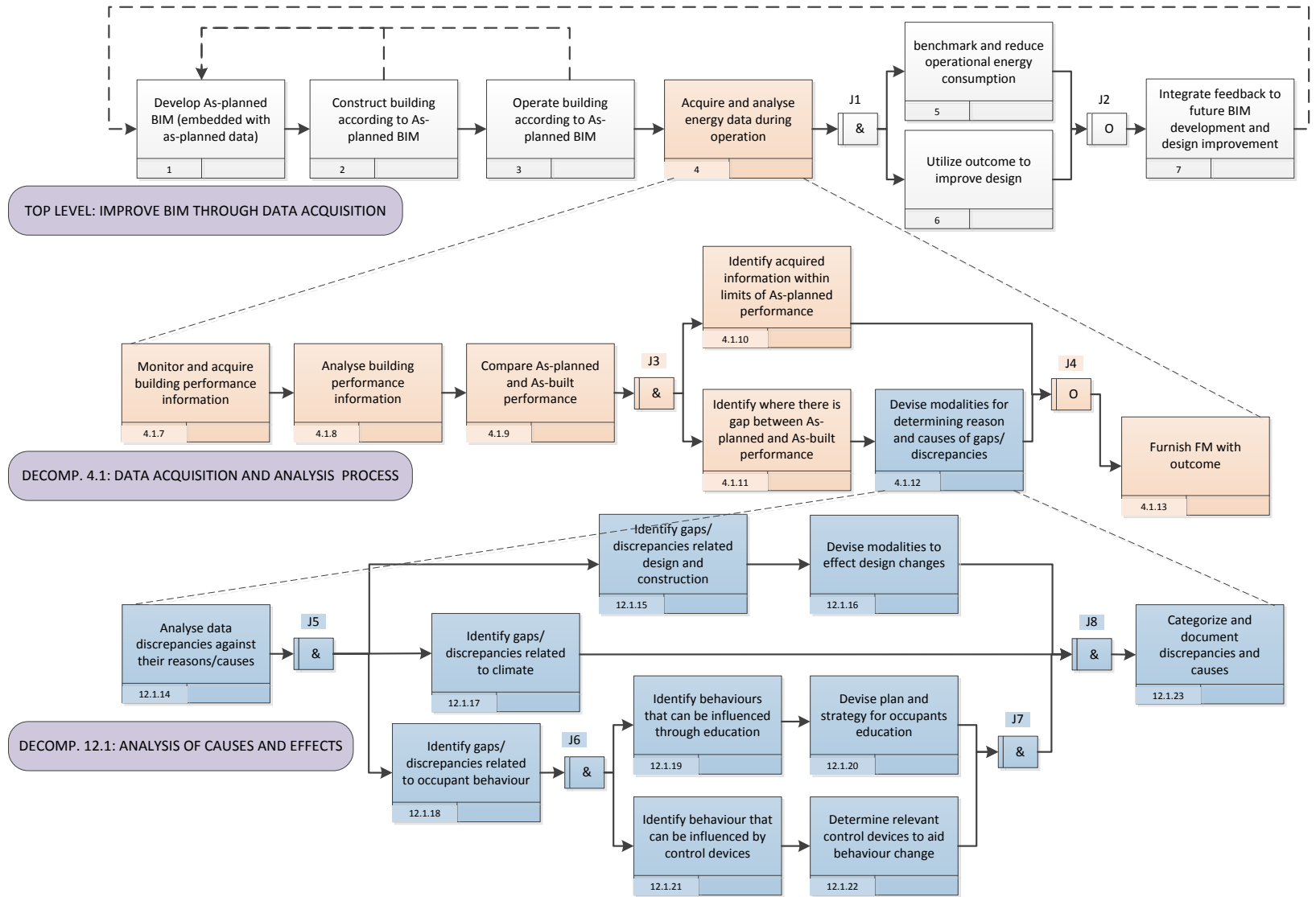
46 The importance of considering the overall consumption level of As-planned performance and
47 As-built performance is worth mentioning. With varying levels of consumption categories, it is
48 possible for the overall consumption level of As-built performance to be less than As-planned
49 performance with some categories of As-built consumption levels exceeding that of their
50 design counterparts. Even if this occurs perhaps as a result of the facility running under full
51 capacity, it is still important to examine the categories of consumption that exceed design
52 benchmark to ascertain causes and proffer solutions for the purposes of improving
53 performance levels.

54 **4.3 Analysis of causes and effects**

55 In this third level (DECOMP 12.1), the reasons and causes of gap/discrepancies resulting in
56 As-built consumption exceeding design benchmarks are determined. Three parallel paths
57 are possible in determining the causes and effects of related discrepancies. First (UOB
58 12.1.15), lapses in design and construction of the building could be causing the problem.
59 Instances could be failure to achieve the desired airtightness around openings such as
60 windows and doors. If such causes are identified, it is possible to proffer remedies through
61 retrofitting and renovation works. Second (UOB 12.1.17), climatic conditions can greatly
62 influence behaviour of building occupants and as such result in high consumption levels. It is
63 expected that prolonged extremely cold periods during the winter will result in higher energy
64 usage for air conditioning and heating. In terms of remedy, not much can be done about the
65 climate and as such difficult to correct discrepancies induced by the climate. Third (UOB
66 12.1.18), reasons why operational energy consumption levels exceed design benchmarks
67 could also be attributed to occupants behaviour. There is some potential to achieve
68 reduction in energy consumption level from this group because of the possibility of using
69 education and technology to help humans adjust or control their behaviours. The framework

70 therefore suggests exploring influencing human behaviour by means of education or the use
71 of control devices based on the nature of the behaviour.

72 Thus, identifying the factors influencing consumption levels is a key element of the
73 framework. The framework sums up that besides factors resulting from building design and
74 construction modifications or errors, the climate of the environment and human behaviour
75 are key contributors to varying levels of consumption. While not much can be done about the
76 climatic conditions, aspects of behaviour can be controlled to achieve reductions in energy
77 consumptions. A further challenge is in the identification of such behaviours and devising
78 modalities to curtail them. The actual practicalities of achieving this requires further research
79 involving field work and falls outside the scope of this paper. It is worth mentioning that there
80 have been research efforts in this direction, albeit, to establish models that appreciably
81 imitate human behaviour in energy simulation systems [29] and identify effects of occupant
82 behaviour on consumption [18, 30].



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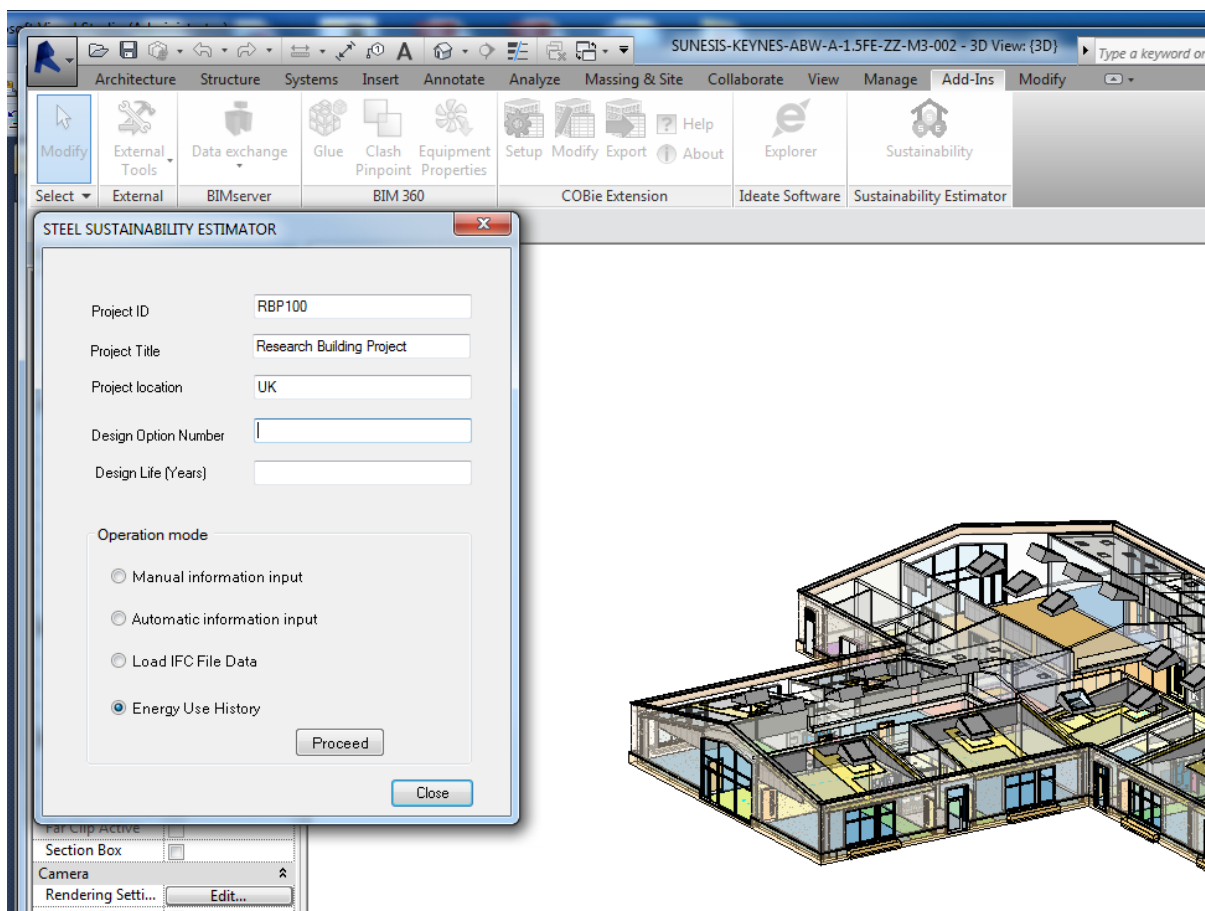
84 Figure 5: Mapping of proposed utilization of BMS data

85 **5 A case illustration of framework implementation**

86 The framework for data acquisition and utilization in BIM is implemented using a prototype
87 as a demonstration of proof of concept. The technicality involved in developing the prototype
88 is explained in this section including a scenario of using the prototype in a real-life project.

89 **5.1 Features of the prototype for data acquisition utilization in BIM**

90 The approach adopted in developing the prototype for data acquisition utilization in BIM is
91 the BIM – Energy Consumption Viewer Plugin Link discussed in Section 2.2. The prototype
92 is developed in Revit 2014. It can be configured to work in Revit 2015 or new versions to
93 come. The implementation of the prototype system was carried out in C# using .NET and
94 linked to the BIM enabled software (Revit 2014). The prototype plugin can be accessed via
95 the external tools link in Revit 2014 IDE. It functions as an extension (See Figure 6) of plugin
96 application of the earlier research work on the sustainability appraisal of structural steel
97 framed building [31].



98
99 **Figure 6: Plugin options selection**

100

101 The prototype has been developed through the iterative testing of system components
102 following the RAD approach. The RAD approach is characterized by increased speed of
103 development and progressive system refinement to achieve early usability. The flowchart
104 illustrating the actions and processes captured in the prototype system is given in Figure 7.
105 Further details of the sequence of events regarding the functions (input and output) of the
106 user (designer) and system are captured in Figure 8. The programme is called through the
107 Energy Use History option of the sustainability Estimation Programme from a BIM enabled
108 environment. On the selection of the project (by name) to examine, the type of information to
109 further explore can then be specified. This offers the option of comparing Design
110 benchmarks and Actual Consumption records or examining various energy consumption
111 categories. These records are extracted by the system from spreadsheets saved in the
112 various project names and containing pre-defined energy consumption data. The
113 consumption categories can be examined for a single project or a combination of projects.
114 The intention of such combination is to compare and contrast trends of similar consumption
115 categories of different projects. The system then displays corresponding output charts; from
116 this point, reports can be produced. The user can switch back and forth between different
117 projects and consumption categories or quit the programme.

118

119 The prototype accesses design data and processed BMS (energy consumption) data saved
120 in MS Excel file formats and expresses abstracted information on energy consumption in
121 terms of 'Design' and 'Actual' performances for buildings. These values are compared at
122 various levels of granularity to investigate waste and encourage the use of appropriate
123 measures to reduce consumption levels and save cost. At the moment, the input data into
124 the plugin need to be provided in Excel file format which requires manual processing of the
125 BMS data. However, there is a possibility that this function of processing BMS data and
126 saving in Excel Format can be done by appropriate energy analysis tools, if they become
127 available. For the purposes of demonstration of concept, we have used manual processing
128 by which we mean programming spreadsheet calculations to transform the BMS data to the
129 required level and format. The resulting spreadsheet data resides in a folder within the
130 solution programme of the prototype and serves as part of its input information for providing
131 requisite energy consumption plots. Currently, the spreadsheet is residing on its own within
132 the prototype environment and not linked to any BIM object. The data in the spreadsheet is
133 rather accessed by the prototype when called up in the BIM environment. Future aspects of
134 expansion will consider automating the processing of BMS data by incorporating this aspect
135 within the prototype. Furthermore, we will explore the possibility of linking processed
136 consumption data to BIM objects to achieve more precise object-information relationships.

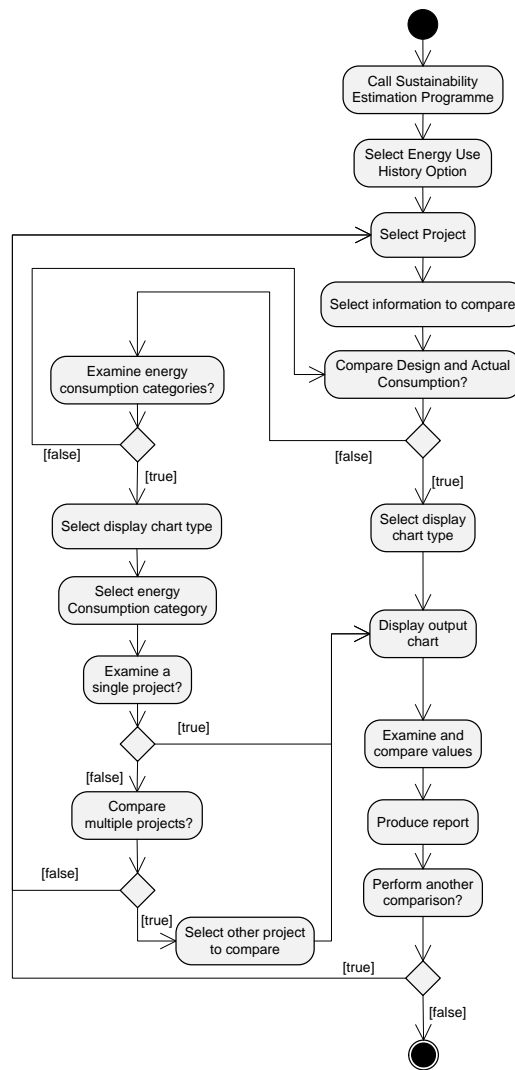


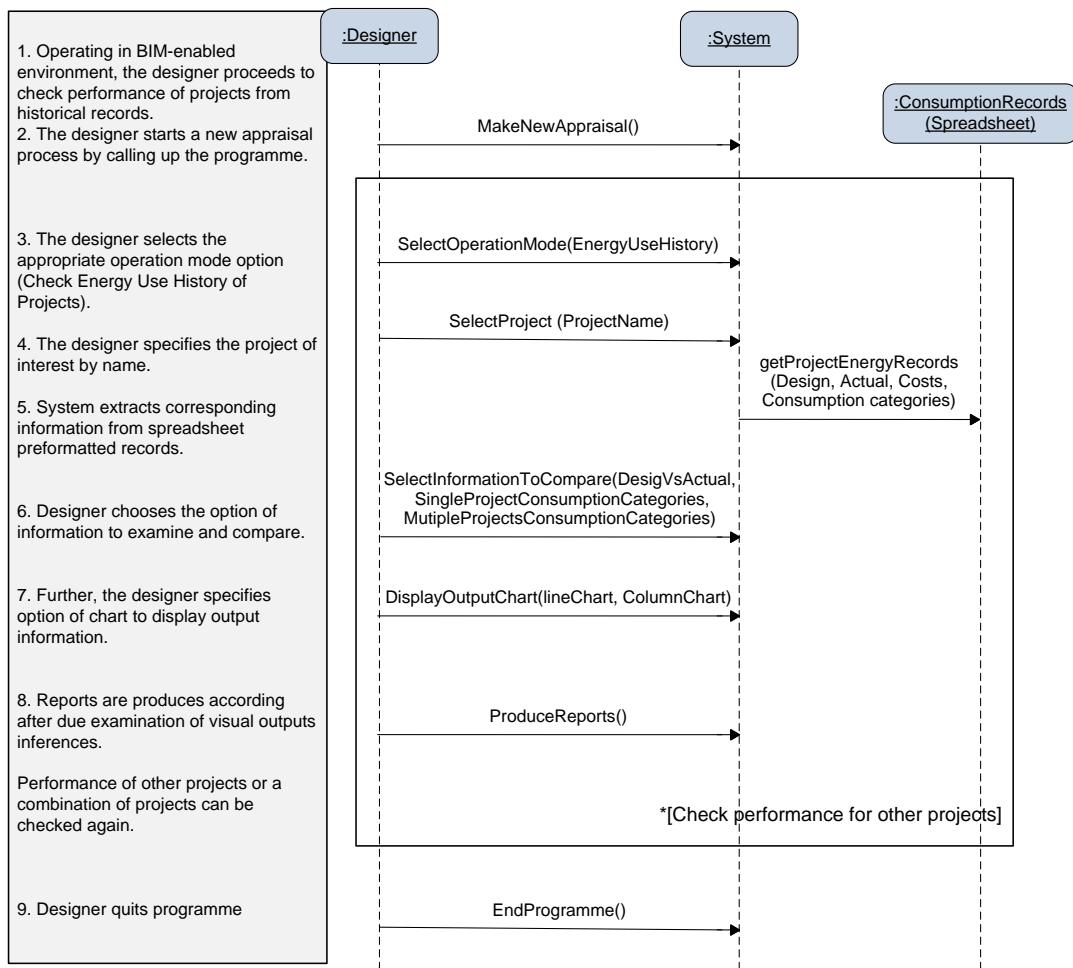
Figure 7: Prototype implementation flowchart

141 5.2 A test case of using the prototype

142 Three projects have been used to illustrate the testing of the prototype. The data from one of
 143 the projects (Project 1) has been obtained as part of a collaborative research project
 144 between a main contractor and a school. The data from the other two projects were
 145 generated as a variant of Project 1 in order to demonstrate the operation of the prototype.
 146 Project 1 is a primary school building in the UK completed and opened for use in October
 147 2012 with a data acquisition system in place and running. Energy consumption data has
 148 been collected and processed in spreadsheets serving as ready input for the prototype. The
 149 spreadsheet resides in a folder within the programme solution of the prototype. The relevant
 150 information were extracted from the spreadsheet and recorded in formats for easy

151 abstraction by the prototype. The example data used in this case is given in Table 2. It is
 152 worth mentioning here that the process of entering data into spreadsheet is generally prone
 153 to errors. In transferring BMS data to spreadsheets, a system to check data fidelity is
 154 important. This may be accomplished through independent revisions but it is much better to
 155 incorporate facilities to automatically transfer streamed BMS data directly to spreadsheets.
 156 The processed BMS data is imported from the spreadsheet into the prototype for further
 157 analysis and displayed in the BIM-enabled environment. Since the prototype can be called in
 158 a BIM-enabled environment, the operation history of consumption levels and design
 159 benchmarks of buildings can be compared.

160



161

162

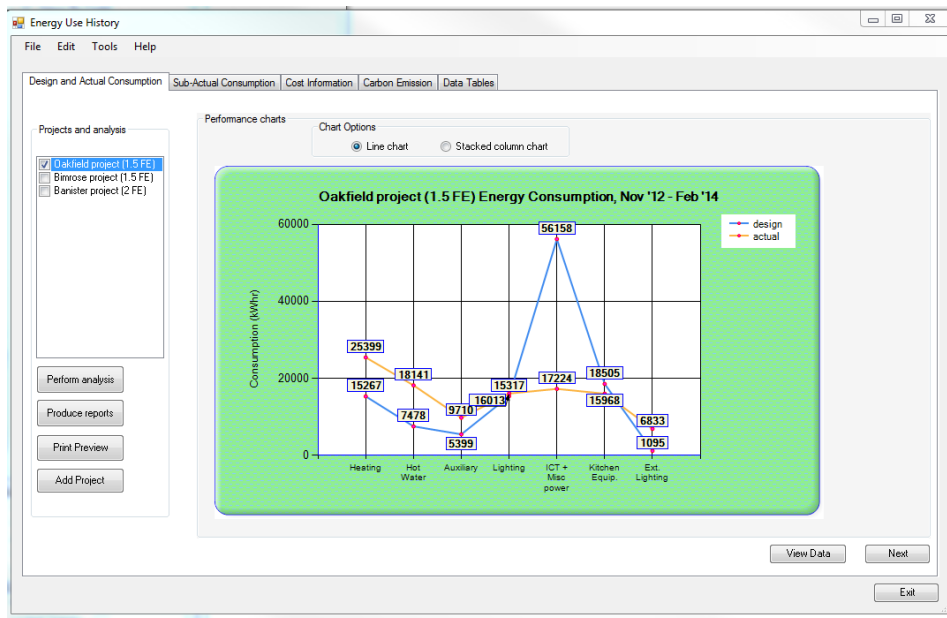
Figure 8: System sequence diagram

Table 2: Processed project consumption data

Description of consumption category		Average daily periodic consumption (kWhr/day)													Consumption for whole period (kWhr)	
		8 - 14 Nov 12	14 - 28 Nov 12	28 Nov - 20 Dec 12	20 Dec 12 - 5 Feb 13	5 Feb 13 - 7 Mar 13	7 Mar 13 - 25 Apr	25 Apr - 3 June	3 June - 11 July	11 Jul - 9 Sept	9 Sept - 14 Oct	14 Oct - 5 Nov	5 Nov - 5 Dec	5 Dec - 25 Feb	Design	Actual
Heating	Heating	95.70	98.62	154.10	118.36	146.56	101.19	27.71	0.00	0.00	17.70	53.16	116.21	118.26	15266.80	25398.81
Hot Water	Hot Water	37.45	44.63	59.58	42.15	65.81	81.69	39.94	42.79	35.27	39.79	36.03	38.46	38.53	7477.95	18140.87
Auxiliary	Auxiliary - general	5.74	-5.05	9.40	6.20	9.27	10.50	3.69	0.98	0.64	2.38	5.73	7.04	8.41	5399.03	9710.50
	Auxiliary - kitchen extract	2.64	2.55	16.38	59.41	53.83	29.02	1.15	2.68	7.26	15.55	1.55	1.04	9.92		
Lighting	Lighting - DB01	1.11	4.82	1.17	0.25	0.68	0.02	6.06	11.39	5.05	14.69	13.05	18.99	13.73	15316.63	16012.84
	Lighting - DB03	48.03	50.56	49.06	33.61	40.22	34.21	31.47	38.86	24.48	43.97	37.58	51.90	41.15		
ICT + Misc power	Small power - DBP03	6.87	7.33	8.24	6.88	7.48	7.56	7.09	8.01	5.05	8.13	6.77	7.47	6.65	56158.49	17223.51
	Small power - DBP04 (Server)	39.28	37.75	46.42	36.77	38.76	37.82	37.68	39.90	30.54	40.31	36.17	40.08	35.94		
Kitchen Equip.	Kitchen Equipment	43.32	41.75	47.52	36.49	42.53	41.23	43.80	45.29	35.81	44.33	41.34	47.90	44.24	18504.98	15968.43
Ext. Lighting	External Lighting	19.56	19.48	24.15	23.66	20.96	16.56	13.09	11.69	13.89	18.66	21.75	23.86	24.00	1095.36	6833.30

164

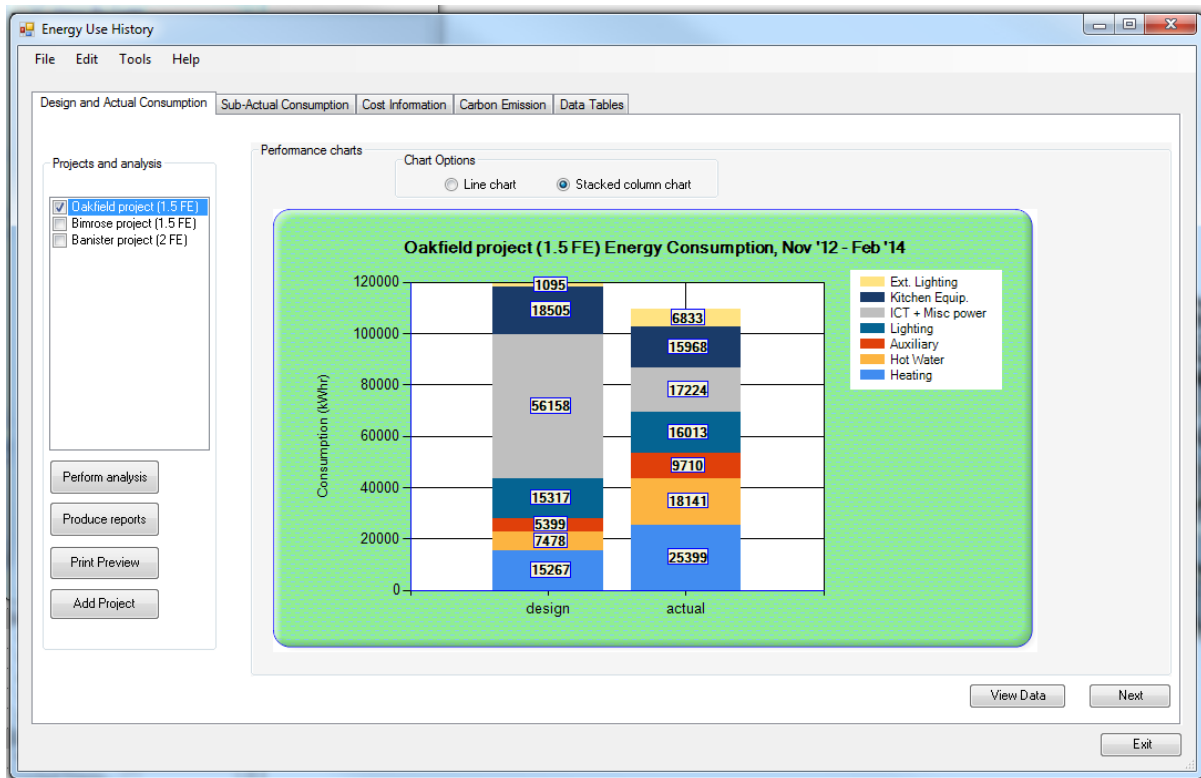
165 Figures 9 and 10 show alternative chart views of the design and actual energy consumption
166 figures (details in Table 2) of Project 1 from November 2012 to February 2014. Similar charts
167 can be obtained for the other projects. Thus, project information need to be entered in
168 prescribed Excel format and loaded into the prototype to appear in the list of Projects and
169 Analysis listBox. The advantage of these charts to designers is that they will help to provide
170 opportunity for quick review of design and performance benchmarks for more critical
171 examination and analysis where required. For example, the designers' attention may be
172 drawn to the Heating, Hot water and ICT sub-consumption categories for further
173 investigation if the respective charts reveal some unexpected outputs. More specifically, the
174 design and actual energy consumptions in Figure 9 show an unusual discrepancy on
175 the ICT + Misc. power category. For ICT + Misc. power, the design value (56,158kWhr) is
176 much higher than the actual consumption value (17,224kWhr) while lower for all other
177 categories. Such revealed discrepancies call for further investigation, the outcome of which
178 can be useful in refining the design or to the team operating the facility. For instance, it
179 could be that the design assumptions for the ICT + Misc. power category may have been
180 over board or the corresponding actual energy consumption is not yet running at full
181 capacity. For either case, further investigation will reveal the true cause of the situation
182 which can become useful information to inform future designs and project delivery.



183

184 **Figure 9: Comparison of Project 1 design and actual (line chart)**

185

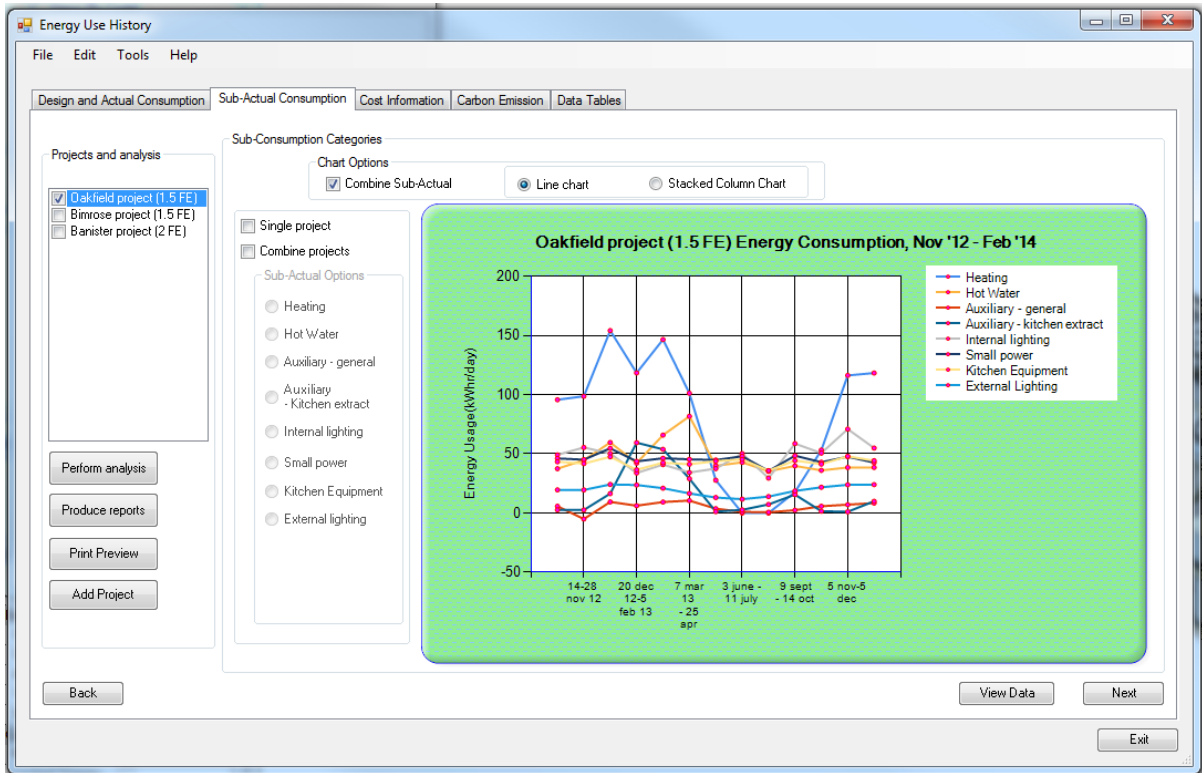


186

187 **Figure 10: Project 1 design and actual stacked column comparison**

188

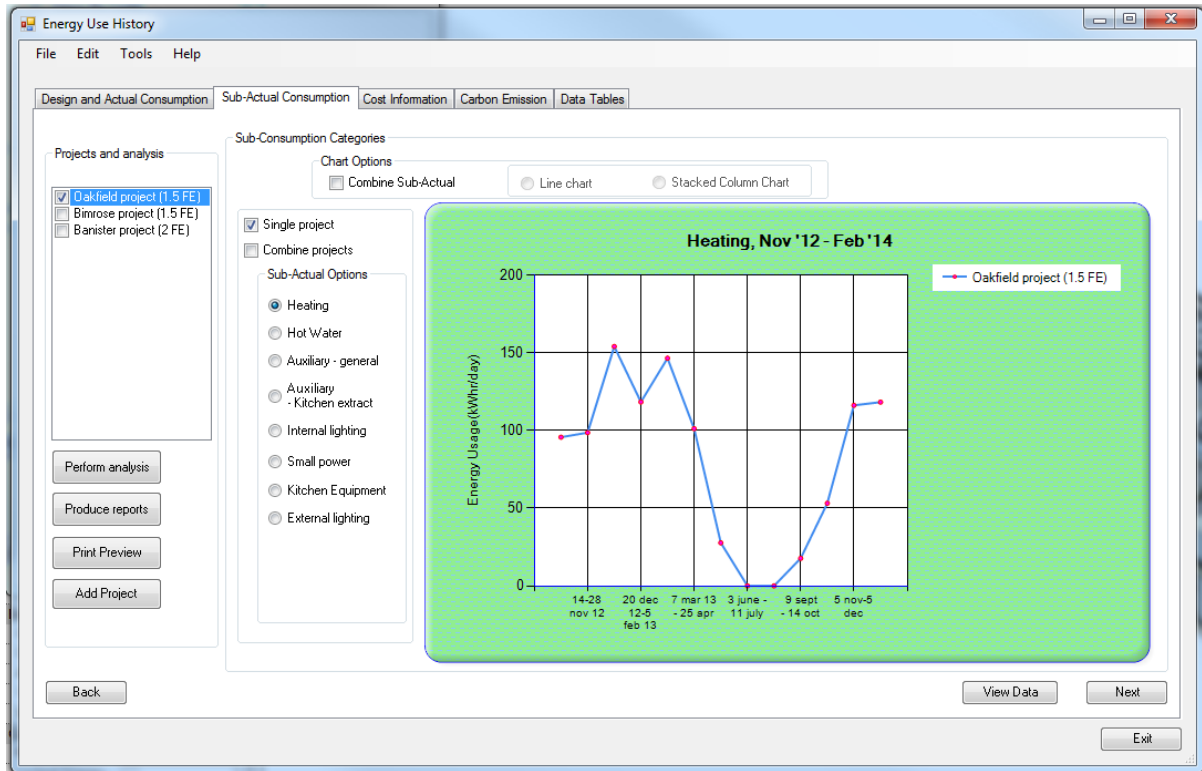
189 Also, it is possible to view a combination of the sub-consumption categories (see Table 2 for
 190 data) as line or column charts as shown in Figure 11. Individual categories of energy sub-
 191 consumption such as Heating, Hot Water, Lighting etc can be further examined (Figure 12)
 192 for each of the listed projects or compared with other projects (Figure 13). Such comparison
 193 has the potential of revealing projects with abnormal consumption trends that warrant further
 194 investigation into possible causes and effects. Further, the prototype can compare
 195 information on energy costs for design and actual consumption of projects. As before, this
 196 can be done for any of the listed projects as illustrated in Figure 14 and also compared on a
 197 project basis (Figure 15). These charts and the underlying data can be viewed and printed
 198 for hard copy recording. The prototype is programmed to compare a number of projects but
 199 illegibility of fonts may become an issue if there are more than 10 projects. Users can
 200 achieve some relative degree of ease in forming BMS data and loading such into the
 201 prototype if the intervals of data collection or streaming from the BMS is similar.



202

203 **Figure 11: Sub-actual consumption categories for Project 1**

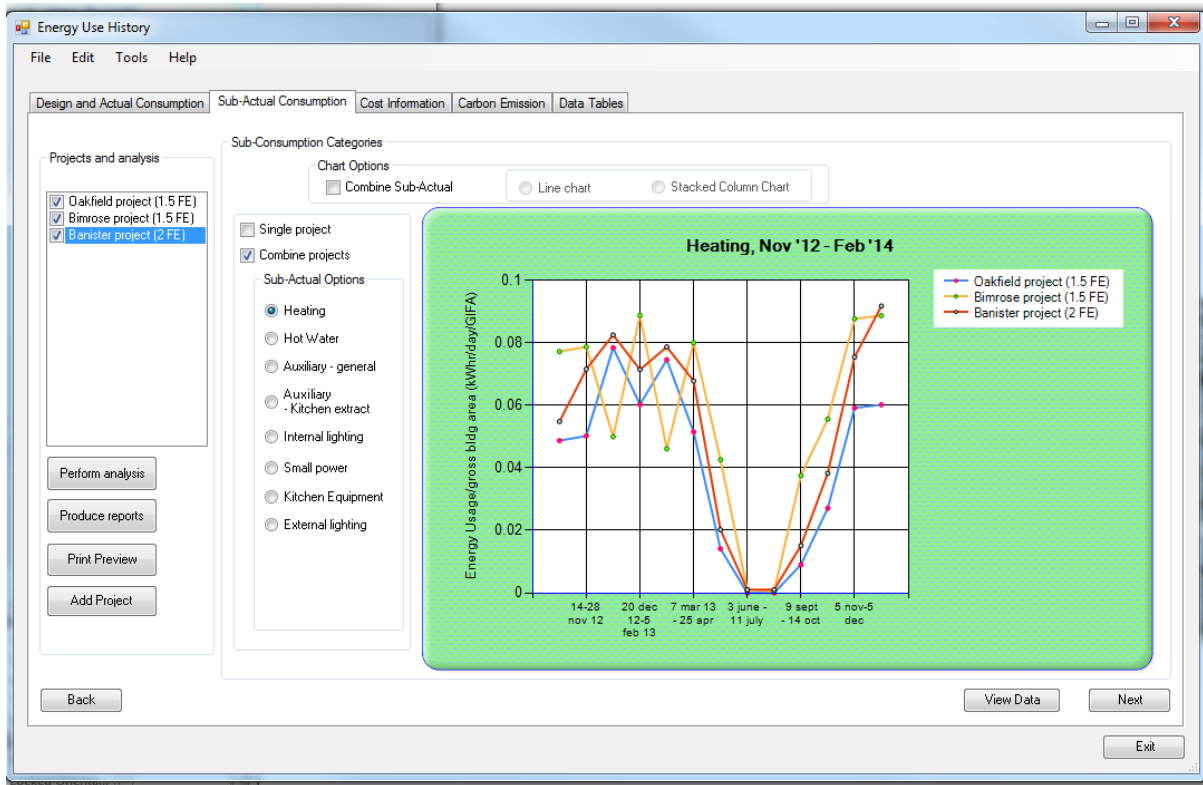
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205

206 **Figure 12: Individual sub-actual consumption category**

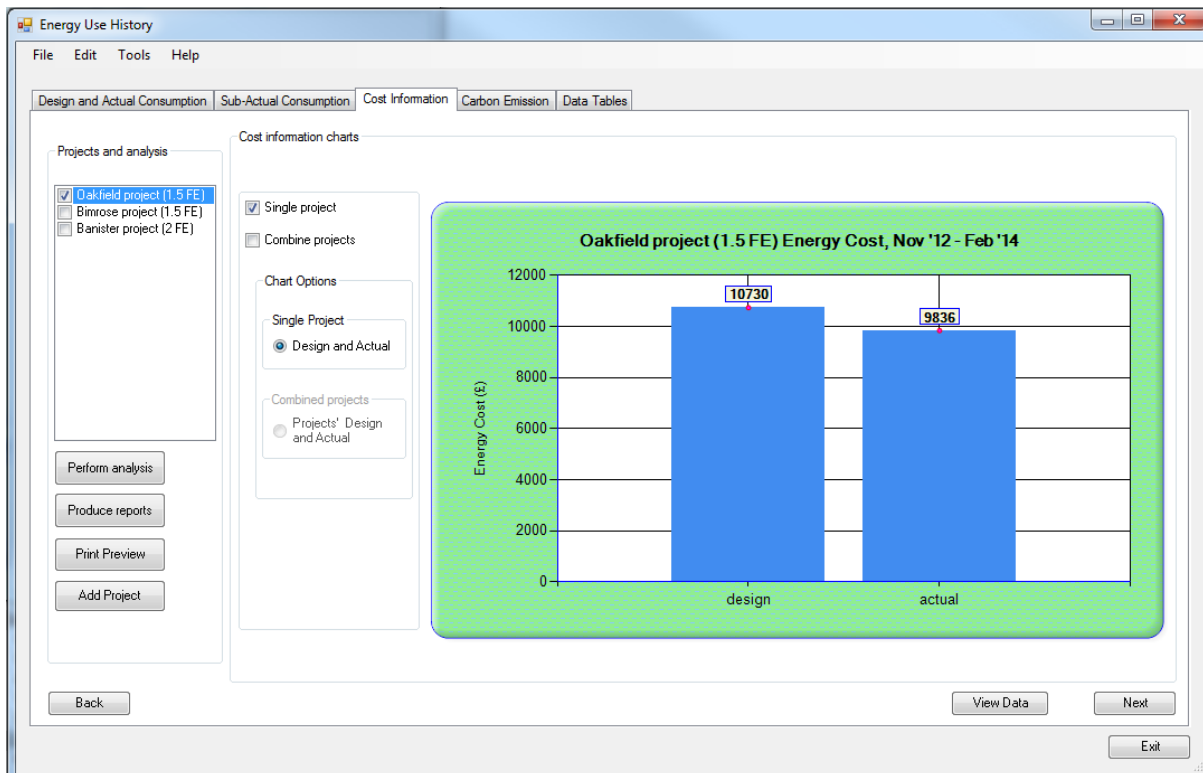
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208

209 **Figure 13: Individual sub-actual consumption comparison of projects**

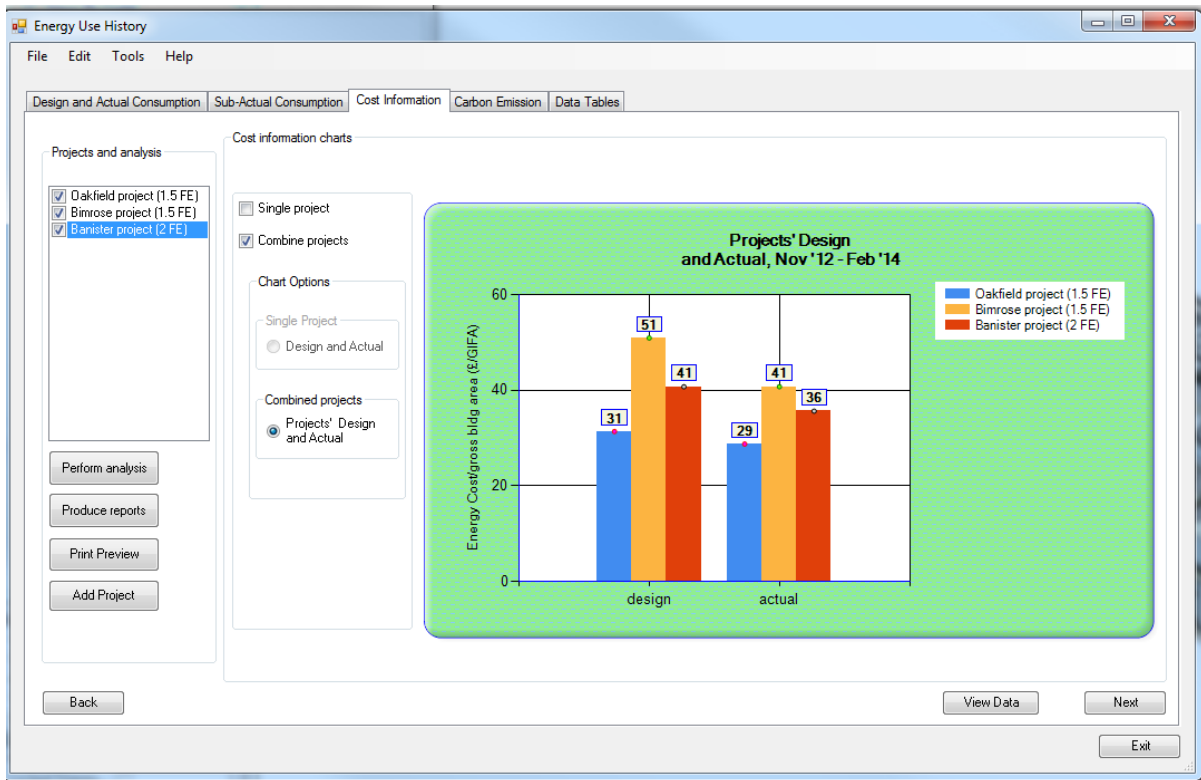
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211

212 **Figure 14: Design and cost actual cost comparison**

213



214

215 **Figure 15: The comparison of projects' design and actual consumptions**

216

217 **6 Limitations and suggestions for future research**

218 At present, the output of the implementation, in the form of a prototype, is tailored towards
 219 turnkey projects handled by the contracting partner of the consortium. However, we are of
 220 the opinion that the findings of this research will be useful to general integration efforts of
 221 building operation and the other phases in the building life cycle. The prototype will be most
 222 suited for turnkey project delivery arrangements and in particular where the same or similar
 223 designs are used for the construction of projects such as estates, campuses and schools.
 224 Another restraint is that BMS data of different projects need to be formatted to similar
 225 structure before loading into the prototype. The challenge is that the intervals at which BMS
 226 data is collected may vary. Some adjustments to data collection intervals may be necessary
 227 in such cases. A pre-defined and consistent data collection framework, which would ideally
 228 be undertaken at the same intervals, be automated and operationalised on the Cloud, could
 229 overcome this challenge.

230

231 In this paper, we suggest taking advantage of BIM technology to enable the feedback of
232 BMS data to earlier project stages. However, there are issues relating to the willingness of
233 clients/building users to allow employing such feedback processes to improve project
234 delivery. A survey [32] of some south-east UK householders in the mid-90s suggests the
235 public is interested in knowing and reducing potential or actual household energy
236 use/impact. The declaration of such, as energy labels, in real estate and property
237 managements circles have been reported to have some influence on the value placed on
238 property [15-17]. As such property owners may be looking for means to be on the good scale
239 of energy declarations on property. Despite this developing incentive, Clarke et al [33] is of
240 the opinion that legislation and enforcements may become the key drivers in the UK energy
241 economy to leverage energy stakeholders pursuing the deployment of sustainable energy
242 efficient systems. The European mandate on the energy performance of buildings directive
243 (EPBD) is relevant here. As an off-shoot of the Kyoto protocol, EPBD was adopted in 2002
244 as Directive 2002/91/EC which requires that an energy performance certificate is made
245 available when buildings are constructed, sold or rented out [34]. This directive touches on
246 all stakeholders in the property market and the extent to which it is implemented and
247 adhered to needs to be comprehensively investigated and regularly updated [34, 35]. In any
248 case, incorporating historical energy performance data from BMS in BIM (as planned and/or
249 as built) will go a long way to contributing to realizing the EPBD.

250

251 While building energy consumption remains a very essential requirement for the functioning
252 of individuals and the community, it is also important that the overall consumption levels of
253 individuals and groups are not made up of a large proportion of consumption categories that
254 can be avoided or reduced. The overall categories of energy consumption levels can be
255 obtained via BMS data which can also be compared to anticipated performance at the
256 design stage. However, such data do not provide any information on why consumption levels
257 in certain categories are low or high, as the case may be, compared to design benchmarks.
258 The challenge in learning from historical energy consumption data when fed back to the
259 digitized building model in BIM environment is therefore in identifying the factors influencing
260 consumption levels and improvising means to reduce their effects. At the moment, there is a
261 tendency to attribute the difference between design and operation performances to user
262 behaviour or low quality of construction resulting from problems such as low levels of air-
263 tightness. It is not possible to verify such attributions with BMS data alone. Achieving certain
264 energy performance standards, e.g. BREEAM, at the design stage does not necessarily
265 guarantee lower energy consumption levels in the building. Further analysis of BMS data to
266 identify areas exceeding design benchmarks and associated reasons is therefore necessary.

267 This constitutes an area for future investigation which is outside the scope of this paper.
268 However, the framework developed in this research can assist in categorizing and
269 streamlining factors contributing to possible performance levels of such identified areas as it
270 mainly allows for the comparison of energy performance of buildings built largely to the same
271 pre-designed scheme.

272 **7 Conclusion**

273 One aspect of concern in emerging BIM applications is how to influence overall project costs
274 and improve sustainable construction practices right from the planning and design stages.
275 This requires integrating various aspects of existing work stages and processes into BIM.
276 However, the incorporation of FM issues into BIM have seen the least patronage even
277 though it is one of the key stages where all the outputs of the concerted efforts of planning,
278 design and construction of the building is put to test by use. There is the existing gap of how
279 outcomes from such tests are fed back to the planning, design and construction processes
280 to contribute to improving the overall project delivery. In the construction sector, the 'big
281 data syndrome' is prominent in the operation phase of the building as a result of the advent
282 of sensing and automated data acquisition technologies such as BMS. There is also a
283 perception that the sector is going to benefit from the availability of large amounts of data,
284 especially if it is integrated into a BIM environment. Although it is true that data, such as that
285 generated by BMS, has the potential to influence overall project costs and improve
286 sustainable construction practices right from the beginning of the project life-cycle; its
287 automated collection, analysis and integration are still problematic. We, however, suggest
288 that these challenges can be tackled with the aid of the modelling approaches and
289 integration capabilities provided by BIM applications as demonstrated in this paper.

290

291 The paper illustrated how building design-operation integration can be achieved by
292 presenting a bespoke framework for incorporating BMS data in a BIM environment. It
293 presented the concept of the framework implemented in .NET framework and interfaced with
294 a BIM-enabled tool. Thus, it made a contribution to closing the feedback loop between
295 operations and design stages of the building life-cycle, which has so far seen the least
296 patronage in practice and in research on BIM. This was achieved in three key steps. First,
297 potential tools for integrating BMS data to BIM and the available approaches to achieving
298 such integration were identified. Then second, a bespoke framework, which incorporates
299 process flow charts and information representations, was developed to utilise information on
300 building energy consumption to inform and improve design and facility management. Third,

301 aspects of the framework were implemented and tested in a software environment in the
302 form of a plugin interfaced with a BIM-enabled tool. Two key challenges of integrating
303 building operation data in a BIM environment, i.e. structuring and analysing the large and
304 unstructured BMS data, and lack of flexibility in configuring off-the-shelf tools to stream data
305 from existing BMS systems due to interoperability challenges, were thus overcome. The
306 emergent plugin tool compares as-planned energy performance with actual energy
307 performance in a single school and across a number of schools that are built using the same
308 scheme. As a result, it establishes whether the delivered assets suffer from 'the performance
309 gap'. In the main, this work bridges some of the existing gaps in harnessing historical data
310 from the building operation phase to assist in building information modelling and design. It
311 becomes a possible first step in making better sense of building energy performance in use,
312 which has the potential to incorporate other factors such as the Climate, building and use-
313 related characteristics and occupant behaviour. Devising a framework for automatically
314 collecting, analysing and integrating data on the last two categories of factors is identified as
315 an area for future research.

316

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321

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