
Attributing In-Use Building Performance Data to an As-Built Building Information Model for Lifecycle Building Performance Management

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Abstract

The construction industry is moving towards a holistic design environment facilitated by Building Information Modelling (BIM), where information generated during design can be used as the basis for operational management of the built asset. However, this information is often left unchanged post-construction. The data generated describing building performance, such as energy consumption, spatial temperatures and equipment performance cannot currently be managed in a BIM environment. Making use of existing data storage mechanisms and tools would enable better management of a buildings energy performance, but existing data management systems fail to provide a framework to do so. This paper forms part of a research project looking at how BIM can be used as a lifecycle building performance management tool, identifying the necessary steps move from towards integration of performance data in the holistic model.

Keywords: Building Information Modelling (BIM), In-Use Performance, Performance Metrics, Industry Foundation Classes (IFC)

1 Introduction

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

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

overcoming such problems are developed in an ad-hoc basis, this continues to be a problem throughout the construction industry.

Use of data describing a buildings spaces and conditioning equipment is one area where the use of BIM to contain descriptive data and manage large amounts of data could support ongoing commissioning and management of a buildings in-use performance. Exploration of the attribution of data to objects (digital representations of building elements describing spaces and equipment) within the building model, and the potential for measured in-use performance data those objects is made, using the industry standard open format Industry Foundation Classes (IFC).

2 Background

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

2.1 Lifecycle BIM and Building Energy Performance Management

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

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

Post-construction, ongoing building performance can also be simulated to evaluate its performance in comparison to initial design intent, or to better understand issues arising in that building. Industry trends show adoption of continuous commissioning for better building control (Hampton et al., 2006) and in-use assessment (BRE, 2013), in conjunction with initiative such as Soft Landings (BSRIA and Usable Buildings Trust, 2008).

BIM tools and capabilities can be used to enhance the building operations process, where possible integrating the BIM and energy modelling into a parallel environment. Here, continuous assessment of building performance can be made based on live conditions within that building for indication of potential faults and issues during use. Attribution of measured performance data to objects within the BIM has been made by Wetter (2010) using the Building Control Virtual Test Bed. This platform enables the co-simulation of actual and predicted performances, utilising the BIM of the simulated building as its basis (O'Neill et al., 2014; Pang et al., 2012). Embedding BIM into this process brings more issues into an already complex multi-program simulation and analysis system, with Bailey et al., (2011) encountering problems with limited data access, lack of interoperability between platforms and the need for data visualisation to get meaning from the vast amount of measured data.

2.2 Data Fragmentation

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

Transfer of information between modelling platforms for different purposes is notoriously difficult (Verstraeten et al., 2008; Welle et al., 2011), and often results in the creation of an entirely new model for a singular purpose, duplicating work and reducing time available for the application

of its results. Reducing work duplication could be enabled through populating and sharing information in a common environment, requiring development of a common development platform suitable for attribution of information from the numerous design stakeholders. The potential for this platform has been explored by Jiao et al., (2013); however, current modelling tools or storage formats are not suited to management using the single model environment. More specifically, IFC (the closest to an open interoperable format working between current tools) has been identified as one “not well adapted [to] the management and the evolution of data” (Vanlande et al., 2008).

2.3 Simulated and Measured Building Performance Metrics

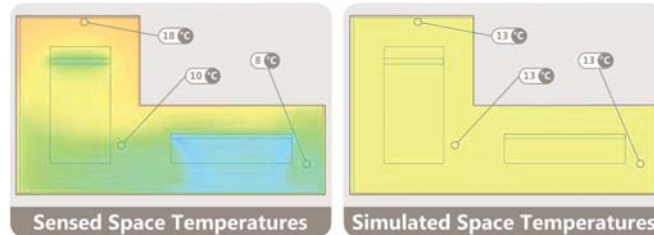


Figure 1 Sensor location and representation of space performance

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

Modelled plant equipment can also be difficult to directly compare to monitored equipment. The BMS records variable dynamic systems dependent on continuously changing criteria while a simulation relies on simplified static data to model a dynamic system, allowing prediction for that criteria specified only at the simulated time. These simplified systems may not lend themselves to comparison with the more complex monitored systems and performance characteristics. For example, sensed space temperature is comparable to predicted space temperature, whereas sensed equipment flow/return temperatures may not be directly compared to predicted equipment energy consumption). The number of variables that can be output by an energy performance simulation program mean a comprehensive list is outside the scope of this work; however, those variables being measured by an example BMS can be used to show what may be linked and used to compare predicted and operational performance. Table 1 shows the potential comparability between these and where sensed data differs from simulation data.

Table 1 Data generation during prediction and operation of a building

	Space-Based Variables	Equipment-Based Variables
Predicted	<ul style="list-style-type: none"> • Ventilation rates • Air temperature • CO2 concentration • Relative Humidity • Internal gains 	<ul style="list-style-type: none"> • Heating plant load • DHW load • Cooling plant load • Ventilation plant load • Humidification plant load
Measured	<ul style="list-style-type: none"> • Air temperature • CO2 concentration • Relative humidity 	<ul style="list-style-type: none"> • System flow/return temperatures • Individual equipment variables (flow/return temperature, energy consumption, valve positions)

2.3.1 Measured and Predicted Variable Comparability

In most cases the direct comparison of measured and predicted datasets is not possible, where predictions from simulation are used either for plant sizing or environmental compliance (Maile et al., 2007). The primary difference between predicted and monitored data are the types of variables being output. Monitored variables represent the resultant conditions from numerous contributing factors, whereas during simulation these contributing factors can be investigated directly.

Indirectly comparable variables may be manipulated into a comparable form (for example simulated cooling plant load being compared to the total energy consumed by pieces of cooling equipment); however, given the variability of systems and complexity of operational modes this becomes unfeasible.

This suggests the comparison of in-use performance metrics (resultant space temperatures, humidity, CO₂ concentration) rather than comparison of individual plant equipment conditioning those spaces would be more achievable. Several issues must be overcome for this to work, not least of all ensuring the accuracy of the simulation to the in-use building. In many attempts to simulate building performance impacted by its embedded plant equipment challenges have been encountered in accurately representing the bespoke in-place systems (Zhou et al., 2013).

2.3.2 HVAC Equipment specific predictive modelling issues

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

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

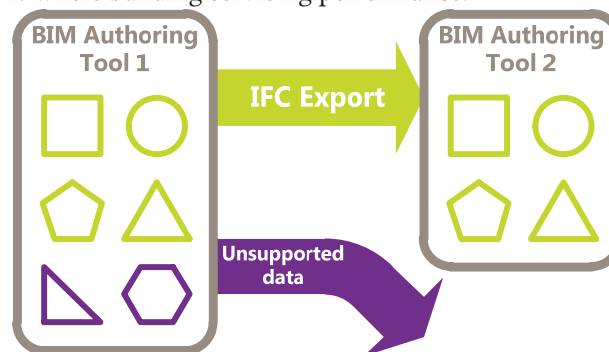


Figure 2 Data loss experienced through IFC "lowest common denominator" approach

2.3.3 Measured Data and Simulated Data Format

In a typical BMS, historical time-series performance data is stored in a SQL server, holding occupant comfort aspects such as space temperatures, CO₂ concentration and humidity in conjunction with system flow/return temperatures, equipment performance characteristics and metered energy consumption.

The format in which the BMS data is recorded means further evaluation and analysis requires several steps to access the necessary data (Ulickey et al., 2010). Initially, the sensors in place throughout the building record operational data at pre-defined intervals. This is then stored within the SQL database and accessed by the BMS interface for local and historical assessment of conditions. Data extraction relies on the user being able to access this SQL database, with the data stored in an intuitive and logical format.

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

2.4 Industry Foundation Class (IFC) Format

The IFC schema (BuildingSMART, 2013) aims to improve interoperability between modelling platforms. The interoperable aspect of the format requires that it forms a lowest common

denominator approach, where information required to describe the building is exported without any proprietary functionality as exhibited by the tool used to create that file (Figure 2).

Objects describing HVAC systems require performance data attribution to move past mere geometric representation, which is possible given IFCs extensibility. However, the IFC framework does not currently allow for a wide range of dynamic data (that which changes over time), using maximum and minimum values for variables during its use in the design process. Static data suffices for design purposes where limit states can be defined, but when moving into the buildings lifecycle where consistently changing operational metrics are prevalent, this becomes less useful.

3 IFC Dynamic Data Storage Feasibility

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

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

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

Following these rules would ensure useful and usable data could be recorded and potentially attributed to objects in a model.

3.1 Recording In-Use Performance in the IFC Schema

The core data schemas around which description of objects within the model and their attributes are managed show provision for the recording of data along a time series (using `IfcPerformanceHistory`). Attribution of these values to objects or spaces defined within the IFC are not yet realised; however, given IFC's object-oriented language there is potential for historical performance data fed from in-place sensors to populate an ongoing performance model (Bazjanac and Maile, 2004; Bazjanac, 2008; Khan et al., 2010). The feasibility of managing time series performance data into an IFC is unexplored, and initial thoughts on this matter suggest that this type of data is not best suited for inclusion within the IFC format given the potential size of datasets and challenges encountered in managing these currently.

3.1.1 Objects in the IFC Schema

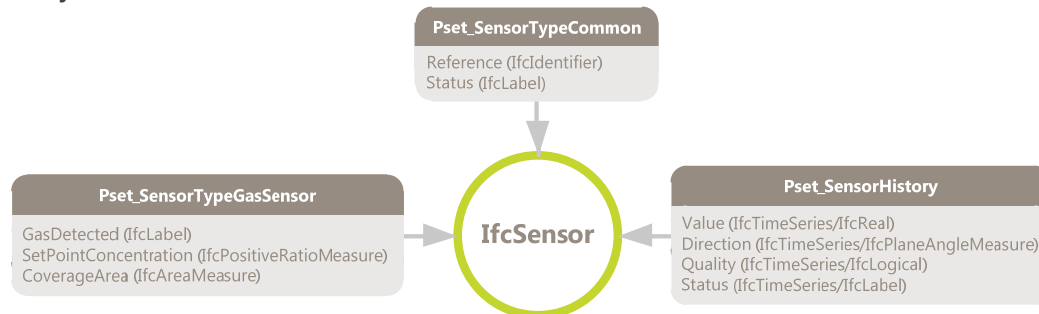


Figure 3 Sensor attributes within the IFC schema

Shared property sets are used to store metadata attributed to objects throughout the entire IFC schema. For example, in the `IfcSensor` object, as with all objects within the IFC, properties shared across all other sensors are defined using `PsetSensorTypeCommon`. Object specific attributes for a

gas sensor are defined within `PsetSensorTypeGasSensor`, with description of the gas being detected (`GasDetected`) and area represented by the sensor (`CoverageArea`) stored as `IfcLabel` and `IfcAreaMeasure` respectively. A static descriptor for the value being sensed (`SetPointConcentration`) is stored as an `IfcPositiveratioMeasure` (Figure 3). These values ascribed to the object within the IFC are used to define an in place sensor within the completed building as part of that buildings control and performance measurement systems.

In conjunction with equipment-specific performance attributes, spaces within the IFC may be attributed performance properties. `IfcSpatialElement` contains property sets describing various performance attributes for that space and as with those descriptors for the sensor objects, these properties are static values for the performance of that space.

3.1.2 Performance Data Within the IFC Schema

Objects with static descriptors are commonly used to transfer information between modelling tools during the design process. Modelled components (if translated correctly) can be viewed and interpreted by software to inform the next stage of building design, and populate datasets such as COBie (Wix, 2008) for object schedules and asset management. The information recorded here is assigned by the modelling tool, and remains in that state until further change. For example, within the `IfcSpatialElement`, the variable `TotalCoolingLoad` within `PsetThermalLoadAggregate` defines the maximum expected cooling load for that space calculated during design. These static descriptors are useful for giving a picture of the building at a single point in time, but not as its operations change throughout the buildings lifetime, where facilities managers may not have the skills to modify them (Volk et al., 2014).

Building energy performance information is not static, and each value relates to a specific time at which it was predicted or measured. As such, static descriptors cannot be used to portray a complete image of that buildings current and past performance for use in indicating potential faults with its operations. A dynamic variable must then be attributed to these measured variables to link with, or be stored within the IFC scheme attributed to its parent object. Several methods of storing time-series data exist within the current IFC schema, described here:

IfcTimeSeriesValue

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

IfcPerformanceHistory

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

Aspects of performance may be grouped into four types, wherein the aspects listed under `IfcProduct` are those most relevant to building energy performance (Figure 4).

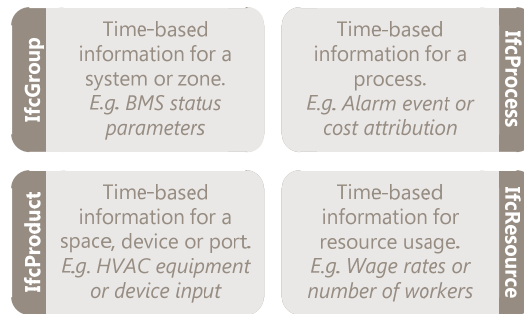


Figure 4 IfcPerformanceHistory Control Assignments

Practical storage of time-based performance information in each of these entities is not currently an in-built capability of commonly used BIM authoring tools, nor is consideration of the model as a platform onto which in-use performance metrics could be attributed. Attempts to relate live data to an existing (or developed) model has been made by Attar et al., (2010) and Khan et al., (2010) where manual correlation between measured spatial performance metrics (pressure, light, current, noise, CO₂, movement, humidity and temperature) was demonstrated using Revit to represent the buildings in-place sensors. These were supported with datasets recorded by the BMS to enhance understanding of performance measurement using a BIM platform. This was achieved under IFC schema 2X3 where sensors were categorized as IfcDistributionElements. Manual corroboration between this static dataset of objects representing sensors, and measurements from those objects real-world counterparts was required to match these, using unique identifiers for each sensor and dataset.

4 Discussion & Conclusions

The concept described here indicates the potential for storing dynamic building energy performance data within an existing IFC format. Such a system would link the operational and design phase of a buildings lifecycle, enabling much closer scrutiny of the often referenced ‘performance gap’. A conceptual data flow model for this system is shown in Figure 5.

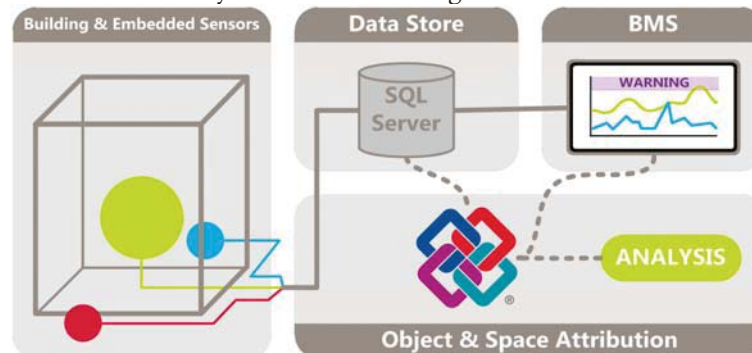


Figure 5 Conceptual data flow model for IFC building performance monitoring and analysis

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

4.1 Challenges to Data Management Using IFC

Size of Performance Datasets

Time-series performance data can consist of several thousand data points, where a single variable measured at 15 minute intervals for a full year results in over 3.5×10^4 values. The number of sensors required to monitor multiple aspects providing valuable performance information, and the number of sensors and frequency of reporting intervals means historical performance databases can be unwieldy. These values may result in datasets less than a Gigabyte; however, computing power available currently still cannot manage this much data in conjunction with an IFC viewing tool, nor would the IFC be shared as easily due to its increased file size.

Accuracy of data/model representation

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

Data Access and Management

Utilising existing datasets for the management of ongoing performance requires access to those datasets and management of them into a form suitable for their analysis. Existing datasets currently employed to record historical performance data store this data in SQL expressions, retrieved via queries. Understanding which field relates to which sensor or time series point is essential to accurately translate this information to a usable format.

4.2 Next Steps

Scope exists for using a BIM environment to support the management of ongoing building performance data, using data storage mechanisms currently employed in cross platform data exchange. To achieve this, changes would need to be made to existing IFC data storage schema, where time-series performance data can be attributed to objects and spaces within the BIM.

The first challenge would be the management of large sets of performance describing data, accounting for thousands of readings throughout a building, and giving insight into its operations, conditioning and overall performance. Using IFC as the basis for large dataset management is currently unfeasible given current computational limitations; however, use of IFC as a reference library to which various uses can reference is more appropriate. Using the objects modelled in this format as the basis for a relational database between design purposed BIM and in-use operational activities would lessen the performance gap through linking historical and live performance metrics with the objects contributing to them. Current BMS's do not adequately link the management of environmental conditioning with the design intent and management of equipment or spaces. Relating design data directly to in-use performance data offers the opportunity to investigate building performance aspects in greater detail, using as-built models to support these continuous commissioning actions.

References

- Aksamija, A., Guttman, M., Rangarajan, H.P., Meador, T., 2011. Parametric Control of BIM Elements for Sustainable Design in Revit. *Perkins + Will Research Journal* 3, 32–45.
- Attar, R., Prabhu, V., Glueck, M., Khan, A., 2010. 210 King Street: A Dataset for Integrated Performance Assessment, in: *Proc. Symposium on Simulation for Architecture and Urban Design*. Presented at the SimAUD 2010, Symposium on Simulation for Architecture and Urban Design, Orlando, FL, USA, pp. 93–96.
- Azhar, S., Brown, J., 2009. BIM for Sustainability Analyses. *International Journal of Construction Education and Research* 5, 276–292. doi:10.1080/15578770903355657
- Azhar, S., Carlton, W.A., Olsen, D., Ahmad, I., 2011. Building information modeling for sustainable design and LEED® rating analysis. *Automation in Construction* 20, 217–224. doi:10.1016/j.autcon.2010.09.019
- Bailey, T., O'Neill, Z., Shashanka, M., Haves, P., Pang, X., Bhattacharya, P., 2011. Automated Continuous Commissioning of Commercial Buildings.
- Bazjanac, V., 2008. IFC BIM-based methodology for semi-automated building energy performance simulation, in: *Proc. 25th CIB W78 Conference*. Presented at the CIB W78, Lawrence Berkeley National Laboratory, Santiago, Chile.
- Bazjanac, V., Maile, T., 2004. IFC HVAC interface to EnergyPlus-A case of expanded interoperability for energy simulation, in: *Proc. SimBuild 2004*. Presented at the 1st National Conference of IBPSA-USA, IBPSA, Boulder, CO.
- Becerik-Gerber, B., Kensek, K., 2010. Building Information Modeling in Architecture, Engineering, and Construction: Emerging Research Directions and Trends. *Journal of Professional Issues in Engineering Education and Practice* 136, 139–147. doi:10.1061/(ASCE)EL.1943-5541.0000023

- BRE, 2013. BREEAM In-Use Statistics.
- BSRIA, Usable Buildings Trust, 2008. Soft Landings.
- BuildingSMART, 2013. IFC4 Official Release Documentation [WWW Document]. Industry Foundation Classes IFC4: Official Release. URL <http://goo.gl/fPLsOc> (accessed 2.14.14).
- Corry, E., Keane, M., O'Donnell, J., Costa, A., 2011. Systematic development of an operational BIM utilising simulation and performance data in building operation, in: Proc. of Building Simulation 2011. Presented at the 12th Conference of International Building Performance Simulation Association, IBPSA, Sydney, Australia, pp. 1422–1429.
- Dossick, C.S., Neff, G., 2010. Organizational divisions in BIM enabled commercial construction. *Journal of Construction Engineering and Management* 136, 459–467. doi:10.1061/(ASCE)CO.1943-7862.0000109
- Ferrari, P.C., Silva, N.F., Lima, E.M., 2010. Building information modeling and Interoperability with Environmental Simulation Systems, in: Sobh, T.M. (Ed.), *Innovations and Advances in Computer Sciences and Engineering*. Springer Netherlands, Dordrecht.
- Hampton, D., Grey, R., Brittain, J., Fox-Davies, T., 2006. *Continuous Commissioning: A Summary Guide*.
- Hitchcock, R.J., Nisbet, N., Wilkins, C., Tanis, M., Hänninen, R., Laine, T., 2012. *Ontology for Life-Cycle Modeling of Heating, Ventilating, and Air Conditioning (HVAC) Systems: Experimental Applications Using Revit* (No. ERDC/CERL CR-12-4). Construction Engineering Research Laboratory, Washington, DC.
- Jiao, Y., Wang, Y., Zhang, S., Li, Y., Yang, B., Yuan, L., 2013. A cloud approach to unified lifecycle data management in architecture, engineering, construction and facilities management: Integrating BIMs and SNS. *Advanced Engineering Informatics* 27, 173–188. doi:10.1016/j.aei.2012.11.006
- Khan, A., Attar, R., Tessier, A., Glueck, M., 2010. *Placing Sensors in the Revit Model*. Digital 210 King.
- Kim, I., Kim, J., Seo, J., 2012. Development of an IFC-based IDF Converter for Supporting Energy Performance Assessment in the Early Design Phase. *Journal of Asian Architecture and Building Engineering* 11, 313–320.
- Love, P.E.D., Edwards, D.J., Han, S., Goh, Y.M., 2011. Design error reduction: toward the effective utilization of building information modeling. *Research in Engineering Design* 22, 173–187. doi:10.1007/s00163-011-0105-x
- Maile, T., Fischer, M., Bazjanac, V., 2007. *Building energy performance simulation tools – a life-cycle and interoperable perspective* (CIFE Working Paper No. WP107). Center for Integrated Facility Engineering, Stanford University.
- McGraw Hill Construction, 2007. *Interoperability in the Construction Industry* (SmartMarket Report). Bedford, MA.
- Moon, H.J., Choi, M.S., Kim, S.K., Ryu, S.H., 2011. Case studies for the evaluation of interoperability between a BIM based architectural model and building performance analysis programs, in: Proc. of Building Simulation 2011. Presented at the 12th Conference of International Building Performance Simulation Association, IBPSA, Sydney, Australia, pp. 1521–1526.
- Morrissey, E., Keane, M., Bazjanac, V., 2004. Specification and Implementation of an IFC Based Performance Metrics to Support Building Life Cycle Assessment of Hybrid Energy Systems, in: Proc. of SimBuild 2004, IBPSA-USA National Conference. pp. 4–6.
- Motawa, I., Carter, K., 2013. Sustainable BIM-based Evaluation of Buildings. *Procedia - Social and Behavioral Sciences* 74, 419–428. doi:10.1016/j.sbspro.2013.03.015
- O'Donnell, J., Maile, T., Settlemire, K., Haves, P., 2013. A visualization environment for analysis of measured and simulated building performance data, in: Proc. of BS2013. Presented at the 13th Conference of International Building Performance Simulation Association, IBPSA, Chambéry, France, pp. 2651–2657.
- O'Neill, Z., Pang, X., Shashanka, M., Haves, P., Bailey, T., 2014. Model-based real-time whole building energy performance monitoring and diagnostics. *Journal of Building Performance Simulation* 7, 83–99. doi:10.1080/19401493.2013.777118
- Pang, X., Wetter, M., Bhattacharya, P., Haves, P., 2012. A framework for simulation-based real-time whole building performance assessment. *Building and Environment* 54, 100–108. doi:10.1016/j.buildenv.2012.02.003
- Rio, J., Ferreira, B., Poças-Martins, J., 2013. Expansion of IFC model with structural sensors. *Informes de la Construcción* 65, 219–228. doi:10.3989/ic.12.043
- Schlueter, A., Thesseling, F., 2009. Building information model based energy/exergy performance assessment in early design stages. *Automation in Construction* 18, 153–163. doi:10.1016/j.autcon.2008.07.003
- Trcka, M., Hensen, J.L.M., 2011. HVAC system simulation: Overview, issues and some solutions, in: Proc. of the 23rd IIR International Congress of Refrigeration. Presented at the 23rd IIR International Congress of Refrigeration, International Institute of Refrigeration, Prague.
- Ulickey, J., Fackler, T., Koepfel, E., Soper, J., 2010. *Building Performance Tracking in Large Commercial Buildings: Tools and Strategies - Characterization of Fault Detection and Diagnostic (FDD) and*

- Advance Energy Information Systems (EIS) Tools (No. Task 4.3 of Project 4), Building Commissioning: Strategies and Technologies for Energy Efficiency. Californi Commissioning Collaborative.
- Vanlande, R., Nicolle, C., Cruz, C., 2008. IFC and building lifecycle management. *Automation in Construction* 18, 70–78. doi:10.1016/j.autcon.2008.05.001
- Verstraeten, R., Pauwels, P., De Meyer, R., Meeus, W., Van Campenhout, J., Lateur, G., 2008. IFC-based calculation of the Flemish Energy Performance Standard, in: *eWork and eBusiness in Architecture, Engineering and Construction*. Presented at the 7th European conference on Product and Process Modelling, CRC Press, Sophia-Antipolis, France, pp. 437–443.
- Volk, R., Stengel, J., Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings – Literature review and future needs. *Automation in Construction* 38, 109–127. doi:10.1016/j.autcon.2013.10.023
- Welle, B., Haymaker, J., Rogers, Z., 2011. *ThermalOpt: A Methodology for Automated BIM-Based Multidisciplinary Thermal Simulation for Use in Optimization Environments* (CIFE Technical Report TR200). Stanford University.
- Wetter, M., 2010. Co-simulation of building energy and control systems with the Building Controls Virtual Test Bed. *Journal of Building Performance Simulation* 4, 185–203. doi:10.1080/19401493.2010.518631
- Wix, J., 2008. *Construction Operations Building Information Exchange (COBIE) Industry Foundation Class Model View*.
- Zhou, X., Hong, T., Yan, D., 2013. *Comparison of Building Energy Modeling Programs: HVAC Systems* (No. LBNL-6432E). Tsinghua University & Lawrence Berkeley National Laboratory.