Automated building energy performance simulation: a review of approaches and outline of research opportunities

Aurelien Bres[1], Georg Suter[2]
[1]AIT Austrian Institute of Technology, Energy Department
[2]Design Computing Group, Center for Geometry and Computational Design,
Vienna University of Technology
Aurelien.Bres.fl@ait.ac.at

Abstract. This paper offers a review of approaches to the automated creation of input data for building energy simulation. Such data may be obtained by translation of available data from architectural and HVAC models. However, a full energy performance model also requires missing data to be completed, either with default values or automated procedures. Following the review, research opportunities for further automation are identified.

1. Introduction

Computational tools that model the variety of processes and interactions relevant to the thermal behavior of buildings have high application potential in building design and operation (Clarke 2001). Despite decades of continuous evolution, building energy performance simulation (BEPS) tools still face challenges when it comes to realizing this potential. Reasons for this are to be found in the simulation model creation workflow, which is considered to be time-consuming and error-prone (Bazjanac 2008). The use of procedures reducing the amount of human intervention for the creation of simulation models, which we will refer to as automation, may address both drawbacks, by reducing the model creation effort and avoiding input errors.

This paper offers a review of approaches that aim to automate the creation of a BEPS model. Organized around the required data, the survey begins with the cases where this data can be translated from existing data, as for geometric data, on which a majority of existing work has focused, before investigating how missing data can be automatically completed. This is followed by a discussion and an outline of research opportunities. Two criteria for the assessment of the reviewed methods are their level of automation and the completeness of the obtained models. In particular, the aim is to create a complete building energy model in the more integrated sense, including the impact of HVAC systems (Barbour et al. 2016, p.1). This paper focuses on data translation and completion, which are relevant in several building energy simulation steps. According to the workflow in figure 1, a simulation user processes information obtained from an architect and an HVAC designer. Part of this existing data can be translated seamlessly into simulation inputs. Section 2 deals with such automated translation, each subsection dealing with a different data domain. In other cases, missing data needs to be completed (Section 3). Default values may be used, notably for constructions and internal loads. More complex procedures might also have to be used, such as for model zoning and for HVAC model creation.

Areas which which are not covered in this review include parametric variations of model attributes, such as building orientation or composition of wall elements, as well as uncertainty analysis and model calibration. The modeling of entire building stocks is not considered, although such a task involves a high degree of automation. Finally, the focus lies on early design phases, for which the potential impact of simulation is assumed to be higher, while time and cost constraints are often incompatible with manual model creation.

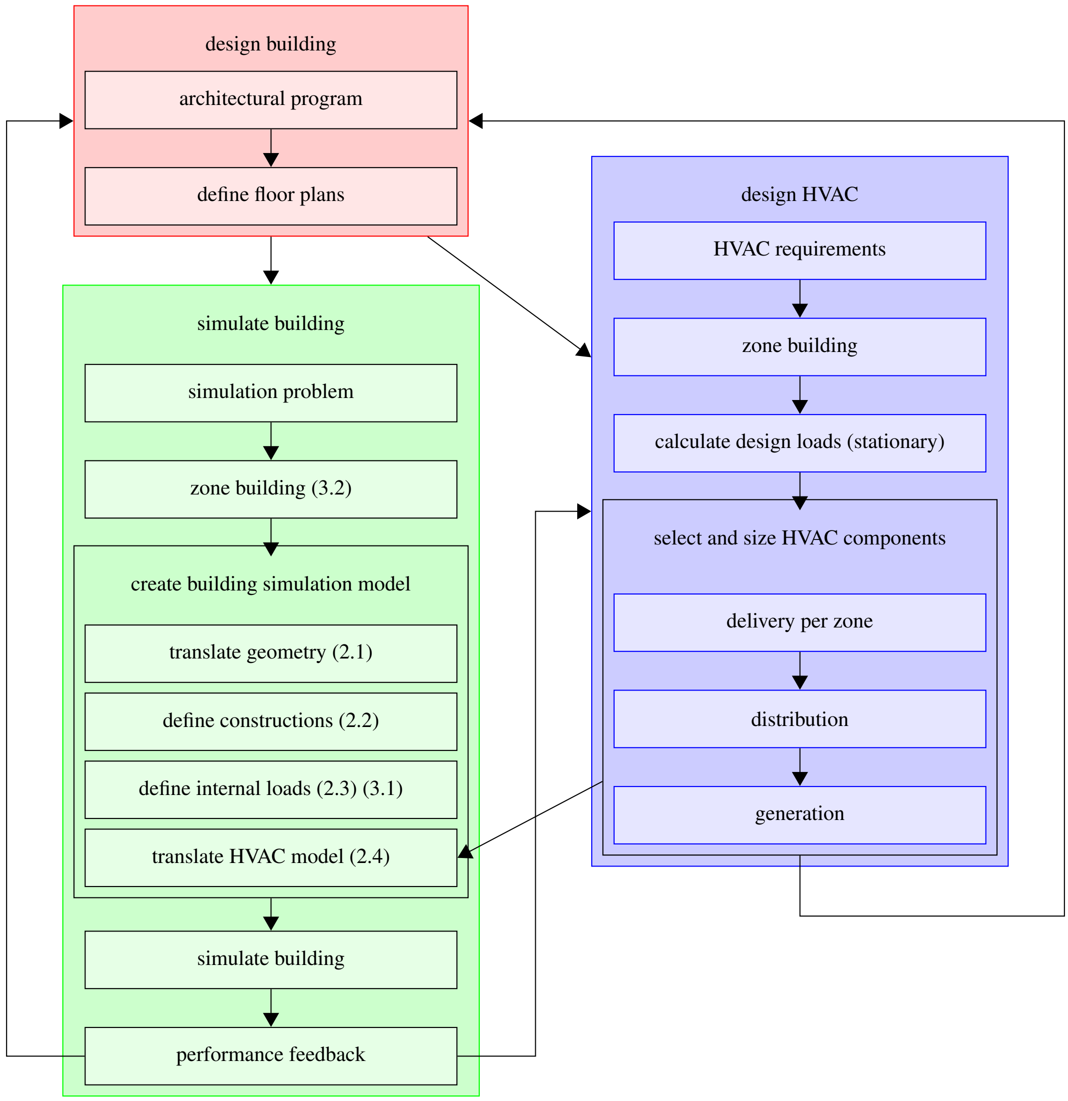


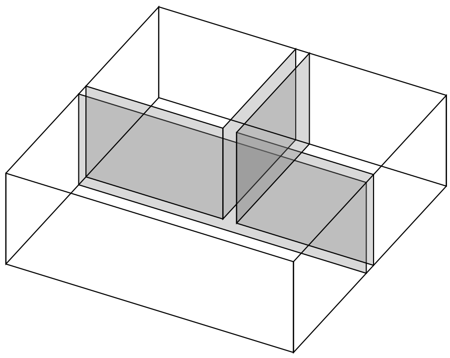
Figure 1: Workflow model for building energy simulation in the design process, with the following roles: architect (red), HVAC designer (blue), simulation user (green)

2. Data translation

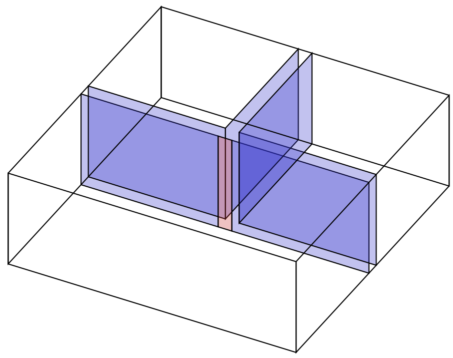
2.1 Building geometry

A three-dimensional description of the building geometry is a prerequisite for dynamic thermal simulation. Ideally, this description is derived from a building information model (BIM), a "shared digital representation of physical and functional characteristics of any built object" (ISO 2010), for instance in a format specified by the Industry Foundation Classes (IFC). Characteristic for the thermal view underlying BEPS is the division of buildings into zones, separated from another by space boundaries. Since the flow through a space boundary is to be consistent, there can only be one zone on each of its sides, and it should be assigned a unique construction.

Hence the need to decompose some space boundaries. The methodology for consistent simulation model creation developed at the Lawrence Berkeley National Laboratory (Bazjanac 2008), based on unambiguous rules for data transformation, the use of IFC-based BIM, and model checking, addressed the problem of geometry translation with the definition of different levels of space boundaries (Bazjanac 2010). Fundamental is the partition of first level space boundaries, modeling surfaces in their maximal extent, to obtain second level space boundaries (level 2a in IFC), in blue in figure 2, which come in pairs through which thermal flow is consistent. This partition may also result in sliver surfaces of higher level (level 2b in IFC), through which no heat flows, but which should be present in the model to ensure closed zone volumes.



(a) Space boundaries of level 1



(b) Space boundaries of level 2 (2a IFC) and 3 (2b IFC)

Figure 2: Space boundaries of different levels according to LBNL methodology (Bazjanac 2010) respectively IFC. Level 1 in gray, level two (2a IFC) in blue, level three (2b IFC) in red

Sources other than a BIM may also be considered for geometry translation. Geometry contained in geographical information systems (GIS) may be only two-and-a-half-dimensional (Reinhart & Davila 2016) or necessitate additional semantic mapping, including, for instance, the transformation of overhanging roof surfaces into shading surfaces (Banfi 2013). Traditional CAD drawings without semantic information require additional steps, particularly for the identification and matching of spaces and surfaces (Jones et al. 2013).

2.2 Construction properties

Heat transfer elements, and possibly heat storage elements, are characterized not only by their geometry, but also by thermal and physical properties required for energy performance simulation. Typically, each construction element is composed of a number of layers of homogeneous materials.

Surface properties can be derived from an IFC model (Giannakis 2015, p.79). The boundary type (internal, external, ground) is indicated by the *InternalOrExternalBoundary* attribute of an *IfcRelSpaceBoundary*. However, information about the thermal properties of construction materials, which could be referred to through the *RelatedBuildingElement* attribute, are not exported by current IFC export tools (Giannakis 2015, p.83). BIM authoring tools feature materials that can be retrieved from databases and assigned to building elements (Autodesk 2011, p.1542). Yet presently they are mainly used to define the appearance rather than physical or thermal properties. Databases such as the "Building Component Library" (Fleming et al. 2012) may allow material and construction data to be exchanged.

Modeling of air-tightness presents additional difficulties. Infiltration rates required for simulation differ from potentially available infiltration rates, which are only measured or defined for a given pressure. Thus, direct translation from building data is implausible. Still, a methodology proposed for the modeling of infiltration (Gowri et al. 2009), which implies the calculation and integration of wind-driven pressures on exterior surfaces for the determination of a wind-dependent infiltration coefficient, could potentially be automated.

2.3 Time series

In addition to static data, building performance simulation inputs also include time-dependent values for occupancy, air change rates, or internal gains due to persons, lights and other appliances. These may be available in different time resolutions, ranging from constant values to high-frequency values for the whole simulation period, quite frequently as hourly schedules defined for one or several day types. In most cases, these values are not directly available, and one may have to resort to default values, as for construction properties. However, several cases may be evoked where time series are available for translation:

- In the case of prescriptive simulation, standard values are to be used for some variables. For instance, the European standard for calculation of energy use for space heating and cooling EN 13790 states that "hourly and weekly schedules of heat flow rate for metabolic heat from occupants and dissipated heat from appliances shall be determined on national basis, as a function of building use, (optionally) occupancy class and purpose of the calculation" (ISO 2008, p.45). For this kind of application, the issue is to determine a building's use together with the occupancy classes of spaces defined by the architect in order to retrieve associated schedules. Attention should be paid to the reference quantities used, e.g. net or gross floor areas, which may vary and require conversion.

- In existing buildings, real measured values may be used as inputs. A co-simulation methodology was proposed for the use of dynamic data in BEPS (Giannakis 2015), allowing automatically generated thermal models to be used for model-based control. Since some quantities (e.g. occupant heat output) cannot be directly measured, correlations between sensed quantities and simulation inputs may be required. For instance, building occupancy may be derived from passive infrared motion detectors, carbon dioxide sensors (Lam et al. 2009), doorway counting sensors, or even classroom scheduling data (Davis & Nutter 2010). Occupant heat output would then be obtained by multiplying the estimated number of occupants by an assumed metabolic rate. This also leads to the topic of calibration, for which automated approaches have been proposed (Robertson et al. 2013).

2.4 HVAC data

Data on existing or planned heating, ventilation and air-conditioning (HVAC) systems serving a building may be available and translated for use in energy performance simulation. While all previously considered data may be be obtained from the architect, HVAC data usually stem from a different source. Thus, automated generation of models for integrated building and HVAC energy performance simulation would require multiple exchanges, as illustrated in Figure 1. Several views are also to be distinguished here:

- HVAC system engineers tend to base system design on static calculations, mostly for the full load case (Vandenbulcke et al. 2012). Moreover, pressure distribution plays an important role in their view of HVAC systems.

- For energy performance simulation, the dynamic behavior of systems, and thus part load conditions, are of primary importance. On the other hand, some processes are assumed to be perfect. For instance, the adjustment of pressure resistances to achieve the flow rates required for energy transfer is mostly not explicitly considered.
- Other disciplines are more concerned with the spatial aspects of HVAC systems, including openings and collision avoidance. The corresponding constraints on dimensions and changes in direction influence resistances in distribution systems and noise effects.

Similar to building data, a common format should be able to support these different views. For energy simulation, the modeling of HVAC systems requires diverse data, including construction properties (e.g. of pipe elements) and time series (e.g. set points and operation schedules). The complexity and diversity of HVAC systems and components contribute to making the integration of information relative to HVAC in BIM a challenging issue.

Despite successive extensions of the "HVAC part" of the IFC data model (Bazjanac et al. 2002, Bazjanac & Maile 2004), IFC data do not yet satisfy the requirements for building energy performance simulation (Wimmer et al. 2014, Liu et al. 2013). In order to support BIM based HVAC definitions in Modelica, Wimmer et al. (Wimmer et al. 2014) resort to the SimModel data model, which can store more relevant data for BEPS than current versions of IFC.

3. Automated completion of missing data

3.1 Use of default values

When required data are not available, some assumptions are necessary to complete the building model. Use of default values for unknown variables is common in approaches for automated BEPS (Smith et al. 2011, Ahn et al. 2014, Leal et al. 2014). For instance, standard constructions may be chosen in function of the building age, and internal loads based on room functions. Default values may be taken out of different sources, such as standards, guidelines, or handbooks, with different levels of credibility. Because of uncertainties in data, it would be reasonable to consider value intervals. Uncertainty and sensitivity analysis have indeed been used in conjunction with BEPS, for instance to predict building performance under future conditions (De Wilde & Tian 2010). One study (Ahn et al. 2014) used uncertainty analysis in order to identify the most significant inputs, and determine which inputs require human intervention in the context of semi-automated simulation.

Default values often originate from the aggregation of large amounts of data. In urban building energy modeling, they may be derived from the abstraction of a building stock into a limited number of archetypes (Reinhart & Davila 2016). Mandatory upper limits for U-values or infiltration in recent building codes represent a case of relatively trustworthy default values. Assumptions often come together with simplifications. For instance, assuming a default construction for external walls implies the absence of differentiation between these walls.

It has been argued that a template format encapsulating non-geometrical properties of building zones could allow default values to be well documented and correctly exchanged, contributing to a fast and consistent setup of BEPS models (Cerezo et al. 2014).

3.2 Zoning

Although fundamental for building thermal and HVAC simulation, zoning has received relatively little attention. Most methods for automated BEPS either equate thermal zones to rooms or settle for a mono-zone building model. An appropriate zoning strategy would depend on simulation goals and available information. A recently presented algorithm (Dogan et al. 2015) creates a partition of buildings whose interior space definitions are unknown, based solely on the building outline. Core zones are found by offsetting the floor outline. Perimeter zones with different orientations are derived from the straight skeleton decomposition of the floor-plan polygon. Using simulation for control purposes, one may use coarser zoning for increased speed (Giannakis 2015, p.100). Grouping spaces for this aim may be achieved with the application of clustering algorithms or other mathematical analysis techniques (Georgescu et al. 2012) on the results of a building simulation with fine zoning.

3.3 HVAC system model

State-of-the-art simulation engines make the simultaneous simulation of building structure and HVAC systems possible. However, detailed HVAC simulation requires a high modeling effort. Moreover, its integration in automated procedures for building performance simulation is not well developed, which can be explained by the translation difficulties described in 2.4. State-of-the-art interfaces such as the Simergy GUI for EnergyPlus (Basarkar 2012) or DesignBuilder (DesignBuilder 2015) use automatic data translation from a graphical view familiar to engineers to a simulation model. The HVAC system is manually assembled from different components linked to each other. Pre-defined templates, autosizing features and the possibility to group zones served by the same type of equipment may speed up this process. It is also automatically checked if the restrictions induced by the EnergyPlus simulation engine are respected. For instance, no more than one set of parallel branches should be present on each side of a water loop. A paper (Ahn et al. 2014) distinguishes fully automated and semi-automated building energy simulation. The latter involves human data entry of given uncertain simulation inputs. It highlights the limits of autosizing and default values for HVAC system variables such as chiller performance coefficients or condenser loop set points.

4. Discussion

The present review has revealed that the different types of data necessary for the preparation of a complete BEPS model are unequally automation-ready.

The translation of geometry has been dealt with extensively. Typical for this the IFC-based space boundary decomposition, the implementation of which should rely on the development of three components dealing with the respective domains of geometry, HVAC and internal loads (Bazjanac et al. 2011). While the first component is already in use, the second one is an interoperable HVAC graphical user interface, comparatively less developed, and the third one is not developed yet. Still, difficulties remain for complex building geometries, such as free-form geometries. Many of the difficulties may be ascribed to the quality of the input model, which could be addressed by model checking in authoring tools and training of model creators (Maile et al. 2013). Others have to do with limitations of the simulation tools. Until now, these can only operate with polyhedral geometries. The approximation of curved surfaces with planar elements should consider the trade-off between quality of the approximation and the increase in run-time and potential errors resulting from numerous surfaces.

Existing methods have paid less attention to other aspects influencing building performance. The need to document and exchange building property data is relevant for automated approaches (Cerezo et al. 2014).

The integration of HVAC systems in automated BEPS only began to be tackled recently (Wimmer et al. 2014, Robert et al. 2014). Since current BIM models lack concepts and properties for a detailed modeling of HVAC systems within building performance simulation, the main approach has been to "extend" the IFC format and complete the corresponding models with custom additions.

The reviewed methods show that a high degree of automated model creation through translation is only possible for some domains. For others, only the use of default values may allow full building energy models to be generated automatically. Exemplarily, simulation parameters, describing the simulation itself rather than the simulated building, are bound to be absent from other data sources. This part of the simulation input can only be determined by the simulation user, taking into account the questioning underlying simulation. Eventually, the objective can be summed up as "trying to set as many intelligent defaults as possible to reduce the number of steps required for a successful analysis" (Smith et al. 2011, p.58). The definition of a successful analysis and the appropriate amount of such defaults remains in most cases an open question.

5. Research opportunities

Based on the review, the consideration of HVAC systems represents an important gap in current approaches to automated building energy simulation. Given the difficulty of translating HVAC models for simulation, and their unavailability in earlier design phases, an alternative approach would be the automated creation of a multi-component structure mapped to the building and its zones, based on key HVAC system variables. In the workflow model presented in figure 1, several steps could be automated with an approximated model. The resulting model could probably give more valuable feedback to designers than is achievable with the assumption of ideal loads. Based on a zoned building model, the system creation process would follow the same steps as in HVAC design, beginning with the calculation of design loads, after which delivery, distribution and generation components are successively determined. Autosizing in currently available tools is performed according to similar steps, but, to the authors' knowledge, lacks any explicit representation of the distribution subsystem. As a result, fully automated pump or fan sizing, which would require pressure drop calculations, is not enabled. Automated procedures deriving the configuration of distribution systems from the building model would be desirable (Clarke 2015), but existing examples thereof are not known to the authors. To begin with, they would require a specification of delivery components and their locations. Existing pipe routing algorithms for different plant types (Guirardello & Swaney 2005) may be used.

More generally, the errors introduced by automated procedures should be systematically investigated. Until now, the literature only offers a very limited number of case studies attempting to quantify such errors (Ahn et al. 2014, Dogan et al. 2015). Comparing these errors to those caused by manual data entry, one could investigate the benefits and limits of a fully automated approach, and if needed pinpoint the most important inputs on which human intervention should concentrate.

6. Conclusion

Until now, approaches for automated building energy performance simulation have mostly focused on the translation of geometric data. The consideration of HVAC systems in automated simulation still represents a gap in the state of the art. Models of such systems could be obtained through translation from a BIM model, or approximated by automated procedures based on building data. Moreover, attention should be paid to the question of zoning and the appropriate resolution of automatically generated building models, as well as to quality control at different levels.

References

Ahn, K.-U., Kim, Y.-J., Park, C.-S., Kim, I. & Lee, K. (2014), 'Bim interface for full vs. semi-automated building energy simulation', *Energy and Buildings* **68**, 671–678.

Autodesk (2011), *Revit Architecture 2011 - User's Guide*, Autodesk, Inc.

Banfi, D. (2013), Energiebedarfsanalyse urbaner rume anhand des semantischen modells und austauschformats citygml, Master's thesis, Technische Universitt Mnchen.

Barbour, C., Zogg, R., Cross, E. & Clark, D. (2016), Research and development roadmap for building energy modelingdraftfor review only, Technical report, Prepared by Navigant Consulting, Inc for the U.S. Department of Energy.

Basarkar, M. (2012), 'Mapping hvac systems for simulation in energyplus', *SimBuild 2012* .

Bazjanac, V. (2008), Ifc bim-based methodology for semi-automated building energy performance simulation, *in* 'CIB-W78 25th International Conference on Information Technology in Construction'.

Bazjanac, V. (2010), Space boundary requirements for modeling of building geometry for energy and other performance simulation, *in* 'CIB W78: 27th International Conference'.

Bazjanac, V., Forester, J., Haves, P., Sucic, D. & Xu, P. (2002), Hvac component data modeling using industry foundation classes, *in* '5th International Conference on System Simulation in Buildings'.

Bazjanac, V. & Maile, T. (2004), Ifc hvac interface to energyplus: A case of expanded interoperability for energy simulation, *in* 'SimBuild 2004, Building Sustainability and Performance Through Simulation'.

Bazjanac, V., Maile, T., ODonnell, J., Rose, C. & Mrazovic, N. (2011), Data enviroments and processing in semi-automated simulation with energyplus, *in* 'CIB W078-W102: 28th International Conference. CIB, Sophia Antipolis, France'.

Cerezo, C., Dogan, T. & Reinhart, C. (2014), Towards standarized building properties template files for early design energy model generation, *in* 'Proceedings of the ASHRAE/IBPSA-USA building simulation conference', pp. 25–32.

Clarke, J. (2001), *Energy Simulation in Building Design*, second edition edn, Oxford: Butterworth-Heinemann.

Clarke, J. (2015), 'A vision for building performance simulation: a position paper prepared on behalf of the ibpsa board', *Journal of Building Performance Simulation* **8**(2), 39–43.

Davis, J. A. & Nutter, D. W. (2010), 'Occupancy diversity factors for common university building types', *Energy and buildings* **42**(9), 1543–1551.

De Wilde, P. & Tian, W. (2010), 'Predicting the performance of an office under climate change: A study of metrics, sensitivity and zonal resolution', *Energy and Buildings* **42**(10), 1674–1684.

DesignBuilder (2015), 'Designbuilder software product overview'. [Online; Accessed 14. July 2015].
URL: *http://www.designbuilder.co.uk/content/view/144/223/*

Dogan, T., Reinhart, C. & Michalatos, P. (2015), 'Autozoner: an algorithm for automatic thermal zoning of buildings with unknown interior space definitions', *Journal of Building Performance Simulation* (ahead-of-print), 1–14.

Fleming, K., Long, N. & Swindler, A. (2012), The building component library: An online repository to facilitate building energy model creation, *in* 'Proceedings of the 2012 ACEEE Summer Study on Energy Efficient Buildings', Citeseer.

Georgescu, M., Eisenhower, B. & Mezic, I. (2012), Creating zoning approximations to building energy models using the koopman operator, *in* 'IBPSA-USA SimBuild', pp. 40–47.

Giannakis, G. (2015), Development of Methodologies for Automatic Thermal Model Generation using Building Information Models, PhD thesis, Technical University of Crete.

Gowri, K., Winiarski, D. W. & Jarnagin, R. E. (2009), Infiltration modeling guidelines for commercial building energy analysis, Technical Report PNNL-18898, Pacific Northwest National Laboratory USA.

Guirardello, R. & Swaney, R. E. (2005), 'Optimization of process plant layout with pipe routing', *Computers & chemical engineering* **30**(1), 99–114.

ISO (2008), Energy performance of buildings - calculation of energy use for space heating and cooling, ISO ISO 13790:2008, International Organization for Standardization, Geneva, Switzerland.

ISO (2010), Building information modelling information delivery manual part 1: Methodology and format, ISO 29481-1:2010, International Organization for Standardization, Geneva, Switzerland.

Jones, N. L., McCrone, C. J., Walter, B. J., Pratt, K. B. & Greenberg, D. P. (2013), Automated translation and thermal zoning of digital building models for energy analysis, *in* 'Building Simulation Conference'.

Lam, K. P., Höynck, M., Dong, B., Andrews, B., Chiou, Y.-S., Zhang, R., Benitez, D., Choi, J. et al. (2009), Occupancy detection through an extensive environmental sensor network in an open-plan office building, *in* 'IBPSA Building Simulation 2009', pp. 1452–1459.

Leal, S., Hauer, S., Judex, F. & Gahr, S. (2014), Implementation of an automated building model generation tool, *in* 'Industrial Informatics (INDIN), 2014 12th IEEE International Conference on', IEEE, pp. 457–462.

Liu, X., Akinci, B., Bergés, M. & Garrett, J. H. (2013), 'Extending the information delivery manual approach to identify information requirements for performance analysis of hvac systems', *Advanced Engineering Informatics* **27**(4), 496–505.

Maile, T., O'Donnell, J., Bazjanac, V. & Rose, C. (2013), Bim-geometry modelling guidelines for building energy performance simulation, *in* 'BS2013-13th International Conference of the International Building Performance Simulation Association', pp. 3242–3249.

Reinhart, C. F. & Davila, C. C. (2016), ‘Urban building energy modeling–a review of a nascent field’, *Building and Environment* **97**, 196–202.

Robert, S., Mazza, D., Hilaire, B., Sette, P. & Vinot, B. (2014), An approach to enhancing the connection between bim models and building energy simulation hvac systems in the loop, *in* ‘eWork and eBusiness in Architecture, Engineering and Construction’, pp. 149–154.

Robertson, J., Polly, B. & Collis, J. (2013), Evaluation of automated model calibration techniques for residential building energy simulation, Technical Report TP-5500-54084, National Renewable Energy Laboratory.

Smith, L., Bernhardt, K. & Jezyk, M. (2011), Automated energy model creation for conceptual design, *in* ‘Proceedings of the 2011 Symposium on Simulation for Architecture and Urban Design’, Society for Computer Simulation International, pp. 13–20.

Vandenbulcke, R., Mertens, L. & Janssen, E. (2012), ‘A simulation methodology for heat and cold distribution in thermo-hydronic networks’, *Building Simulation* **5**(3), 203–217.

Wimmer, R., Maile, T., O’Donnell, J. T. et al. (2014), Data-requirements specification to support bim-based hvac-definitions in modelica, *in* ‘BauSIM 2014, Aachen, Germany, September, 2014’.