Building information models as input for building energy performance simulation – the current state of industrial implementations

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ABSTRACT: The presented work analyzes interoperability, reliability and usability of current industrial implementations that aim to provide a dataflow between Building Information Models (BIM) and software tools for Building Energy Performance Simulation (BEPS). Therefore an idealized data exchange model between the domains BIM and BEPS is introduced. The model includes various data areas that are relevant for building energy performance simulation. On the basis of the idealized model, the interoperability of currently available BEPS tools and architectural BIM software is tested. The results gained from test suite show that the information exchange takes place, however, the direct transfer of the resulting thermal model of the building without manual editing is not possible. The use of BIM Models for simulations requires an understanding of the limitations. The implementation of interoperability has a point-like character and requires further development. In spite of there is mostly a possibility to transfer geometry of building, this is not the only data needed for simulations, the supplementary information is also to be involved in exchange.

1 INTRODUCTION

The sustainability of buildings is not just an empty phrase used in the architecture, engineering and construction (AEC) sector, but is already implemented in sustainable building standards all over the world. To ensure standards compliance, BEPS software tools are used to assess the energy performance and thermal or lighting characteristics of a building. The information is used to assist proper decision-making and improve processes for providing necessary building data (Azhar et al., 2009).

BEPS can be used at different levels of detail throughout all phases of the planning and design process, for new buildings, retrofit projects or even redevelopments. The ability to compare different design options is one of the major advantages of using BEPS. The two main criteria for evaluation are the thermal comfort of occupants and energy consumption (Maile et al., 2007). However, BEPS requires a large amount of valid data to run accurately. To perform an energy-performance analysis, specialist engineers currently gather and combine 2-D drawings, material data and other information to (re)construct the simulation model in the respective software. This process is very time-consuming, often requiring more time than is available during the design process (Osello et al., 2011). Consequently, designers may make arbitrary decisions or assumptions that are often poorly documented. Moreover, if only a small part of the data is invalid or inconsistent, the results of the simulation are no longer credible and acceptable (Bazjanac, 2008 and 2009). Therefore, the ability to integrate BEPS into the BIM-workflow is a desirable next step. The use of BIM is itself comparatively new as a workflow in the design and construction of buildings. A BIM model defines a digital three-dimensional model of the building, which serves as the data exchange basis for the BIM-workflow.

Connecting architectural design and energy analysis makes it possible to validate energy consumption and occupant comfort in a building at different stages of the design process, even in early design phases, where the most critical decisions are made. However, BEPS tools based on BIM-models are not currently intensively used in the AEC industry. For this reason we investigated the current state of industrial implementations and compared this with an idealized data exchange model.

1.1 *Building Information Modeling for sustainability*

The term *BIM* is used in the AEC industry to describe the use of computer-based models and simulation for both existing and new buildings throughout the design process. According to the principles of BIM, it can be used in all disciplines related to the building; i.e. also for BEPS. The building information model created during the BIM process contains all the data required for conducting accurate BEPS. Furthermore, in this methodology the information flow is not just in one direction, but can also accommodate the feedback of simulation results to the building information model for further use in other applications (Kumar, 2008).

Although the use of integrated processes from the BIM methodology is currently not weighted highly in sustainability standards (e.g. in the German DGNB (2008), where it is only rated as a sub-category under process quality), it does bring additional benefits in the assessment of building quality, including: (1) ability to undertake optimization strategies in early design stages due additional knowledge level from databases, automated analysis and simulation; (2) documentation of design decisions; (3) exact calculation of costs for "more sustainable" designs; (4) better transparency of decision-making for customers leading to better acceptance and understanding; and (5) makes it possible to use the information in the building use phase for facility management (FM) and monitoring. This together creates a significant opportunity for society to achieve more sustainable building construction processes and higher performance facilities with fewer resources and lower risks (Eastman et al., 2011).

For this reason BEPS tools are increasingly used today in the context of BIM to study the energy-saving potential of buildings and the thermal comfort of their users. Taking into account the significant number of various architectural and BEPS software, it is valuable to consider and analyze the limits of applicability of existing software solutions for different simulation cases as well as the usability of the tools.

2 RESEARCH METHODOLOGY

We began by examining the possibilities of data flow and model exchange between BIM and BEPS. We modeled and elaborated the theoretically required data flow from a BIM model as the input information for carrying out simulations for further analysis.

The flow diagram illustrated in Figure 1 represents an idealized model of the data exchange between domains. The model includes various data areas that are relevant for BEPS. This information provides the input for subsequent simulations and calculations, and therefore there is a need to accurately systematize and classify such information, to ensure a complete and consistent process within the information flow. The data flow model divides the relevant information for BEPS purposes in the BIM-Model into five data fields.

On the basis of the data flow model, the interoperability of existing BEPS tools and architectural BIM software was verified using a test suite. The analysis investigated feasible points of linkage and the integration potential of energy simulation tools and BIM, showing actually achieved performance and also limitations.

3 CURRENT STATE OF RESEARCH

Building information modeling is nowadays actively integrated in the fields of architectural planning, civil engineering for computer-aided visualization, automated drafting, quantity and cost analysis, clash detection and other activities (Eastman et al., 2011). However, this method is still only rarely used in the field of environmentally-friendly building, although more research is increasingly being conducted in this area.

For example, the geometry transfer development from an architectural BIM tool to the simulation software is an active area of research (Hitchcock & Wong, 2011), including the creation of data mapping schemes (Cemesova et al., 2013).

Geometry transformation based on the IFC (Industry Foundation Classes) file format has been developed for the EnergyPlus simulation engine (LBNL, 2014). The implementation is based on software solutions such as the "Geometry Simplification Tool" or "Space Boundary Tool" (SBT), which translates the geometry of the IFC supporting architectural tools for energy analysis applications (Cemesova et al., 2013). In the given case SBT is used as preprocessor providing input data for the EnergyPlus simulation engine.

SimModel, on the other hand, is an XML-based data model specified especially for the simulation domain. SimModel is largely a union of the IFC data scheme and the input data scheme for EnergyPlus. SimModel is used as a basic data model of Simergy, which is a graphical frontend for the EnergyPlus engine (Simergy, 2013).

4 AN IDEALIZED DATA EXCHANGE MODEL

Previous research has identified six stages in a data exchange process from the building information model to simulation software (Maile et al., 2007). These stages are:

1. Determination of the location of the building site so that the model can be linked to location-specific climate information;
2. Defining the geometry, constructions, materials and spaces of the building;
3. Assignment of the space objects to thermal zones;
4. Allocation of space and lighting loads;
5. Definition of the technical building systems and their components;
6. Execution of energy simulation.

The conversion process of the model geometry usually involves a certain amount of pre-processing and post-processing. Pre-processing is the preparation of the raw data from BIM software, for example, the deletion of irrelevant data for simulation elements or spaces. Post-processing includes data mapping or allocation of elements between the IFC and the internal model of the simulation tool. However, problems can occur during this process, for example, the automatic simplification of walls sometimes leads to holes and inconsistencies in the thermal model (Cemesova et al, 2013.).

Based on these definitions of the geometry, the spaces should be grouped into zones. In the next step, the space loads for the corresponding specific space types from the BIM model must be imported and assigned. Before the simulation can be performed, the technical systems of the building and their relevant components must be defined. This can be done either by manual user input or semi-automatically by importing HVAC information from the central BIM model. After these additional simulation parameters (such as numerical tolerances, begin and end time of the simulation, etc.) have been entered, the simulation is performed (Maile et al., 2007).

The introduced idealized model shows the data exchange between the BIM-Model and the BEPS domain, covering and describing the information requirements imposed by the simulation software. In order to analyze existing solutions and ways of data exchange the idealized model is used as a template that also yields the assessment criteria for the test suite. Using an idealistic and abstract model makes it possible to identify the potential weaknesses and any missing data after the export or import procedures.

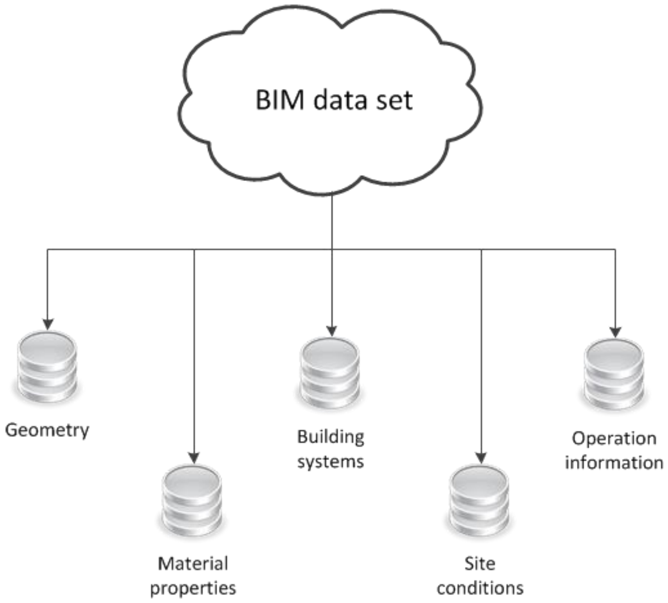

Figure 1. BIM data set and interaction layer.

The total amount of data contained in a BIM-Model is known as the BIM dataset. From this dataset the relevant data to be transferred to BEPS must be extracted. This data is referred as an interaction layer between two domains. The model includes various data fields that are relevant for BEPS. These were identified as:

- geometry,
- material properties,
- building systems,
- site conditions
- building operation information

A meaningful building energy performance simulation requires the use of elaborate simulation software, and large amounts of information as input data. The required data describes the geometry of the building in the simulation, technical equipment and systems of the building, lighting and electrical systems and their schedules, usage type of the building and number of persons, weather conditions for the simulation and more (Bazjanac et al., 2011).

5 CURRENT EXCHANGE SCENARIOS

The current way of working in the field of BEPS involves an architect who designs the building, and an energy expert who has to manually re-create a thermal model using analysis software. This person usually also has to fill in any gaps in the data. Automating data exchange modifies the previous approach by employing a single building model, which leads to further time savings, a reduction in errors to more reproducible simulation results. Since a BIM-model is regarded as a database, when we use and interpret only the relevant parts of the dataset, we adopt a particular view. The exchange of building data is based on an alternation between different views of the BIM-Model, making it possible to analyze data for various fields of activity. In the field of BEPS, the architectural view is converted into a thermal view of the building model. This transformation is needed for several reasons. For example, software tools between which data needs to be exchanged, often have a different internal building model representation. Hence an explicit way of mapping of model objects and concepts between modeling schemes is required (Wilkins & Kiviniemi, 2008).

5.1 *The impact of BIM on the BEPS domain*

A BIM-model is a good practical implementation of a basic data container. Data for different purposes can be extracted from this container, such as daylighting analysis or the calculation of transmission heat losses. The BIM-model provides the ability to store data centrally, avoiding data redundancy and repetition. Planners are able to improve their building design iteratively to see if changes to the design affect the results of an energy simulation in real time, for example, the energy demand, in a building model. However, research on the interoperability of BIM and simulation tools still reveals many unresolved problems and tasks (Osello et al, 2011; Moon et al, 2011; O'Donnell et al, 2011).

Investigations indicate that data is transmitted within the BIM methodology using the IFC schema or gbXML schema. The advantage of the gbXML schema is that it is supported by many BIM and energy tools (Moon et al., 2011). However, the IFC schema is the only public, non-proprietary and well-developed existing data model for buildings and architecture (Eastman et al., 2011) that exists today. The primary benefit of the IFC format is that it has a broader and more advanced area of application than gbXML (Cemesova et al., 2013).

5.1.1 *Green Building XML (gbXML)*

Green Building XML (gbXML) was developed especially for data exchange for BEPS. It has existed since 1999 and is now available in version 5.11. It aspires to become an industry standard and software vendors such as Autodesk, Bentley and Graphisoft now also support the format.

The benefit of gbXML is that is an open source format that is based on the widely-used XML standard and is therefore easy to understand and implement by BEPS software developers. This helps designers concentrate on their main work – the design of usable and sustainable buildings – without having to think about data exchange (Moon et al., 2011). The disadvantage of gbXML is that it comprises only part of a building information model, therefore necessitating conversion to and from other formats such as IFC.

[1] Referenced as GSA-003 at http://www.blis-project.org/IAI-MVD/.

5.1.2 *Model View Definition – Building Energy Analysis (MVD-BEA)*

Where the IFC is used to specify the building information model as a whole, different views of a BIM models are defined as Model View Definitions (MVD). Model View Definitions contain a subset of data provided by the IFC as previously defined by Exchange Requirements (ER, i.e. the data that has to be exchanged described in general, not related to IFC).

There is already a MVD description for BEPS data exchange for the current certified version of IFC, version 2x3; the MVD for Concept Design to Building Energy Analysis (BEA)[1]. The MVD-BEA specifies the different IFC components required for energy analysis, including site, building and space information from model domain, geometry of the main IFCbuildingElements (like walls, windows, curtain walls, etc.), from the architectural domain, HVAC systems from the mechanical domain and electrical power and lighting systems from the electrical domain. Nevertheless, some information is still not provided by MVD-BEA or even IFC, as illustrated in figure 2. The newly introduced version of IFC, version 4, enhances the recent data required for BEPS and will hopefully result in the adoption of a new MVD-BEA, although this has not yet been implemented in any software available on the market. The advantage of using the MVD-BEA is that it can directly access information from the building information model without any conversions. Currently, however, none of the commercially-available BEPS tool support input from the IFC format.

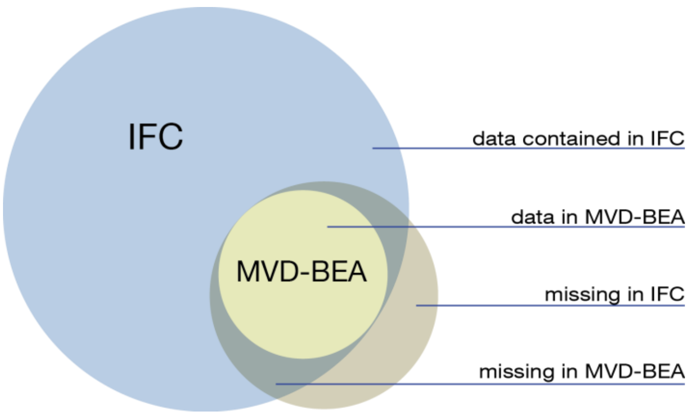

Figure 2: Different levels of implemented data in IFC necessary for BEPS. Some data is contained in the IFC data-format but not covered by the MVD-BEA and other parts are also missing in IFC itself.

6 SOFTWARE TESTS

6.1 *Purposes and structure*

The aim of the tests includes an estimation of the applicability of the data flow model to concrete software solutions for building energy simulation. The test procedures are documented by comparing them with an idealized dataflow model (see section 4).

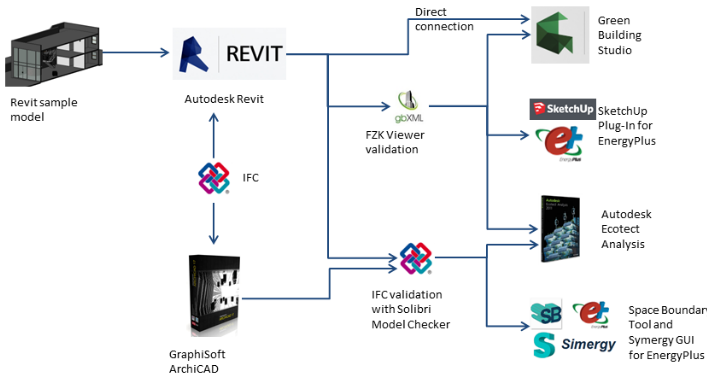

Figure 3. Structure of the test suite.

The software tools used in the test suite are Autodesk Revit (Autodesk, 2014a) and Graphisoft ArchiCAD (Graphisoft, 2014) as architectural BIM solutions and Green Building Studio (GBS), Autodesk Ecotect (Autodesk, 2014b, 2014c) and the EnergyPlus (EnergyPlus, 2014) simulation engine as tools for building energy performance simulation. Three user interfaces for EnergyPlus have been considered, namely the Space Boundary Tool (SBT), a SketchUp plugin (EnergyPlus, 2014) and Simergy (LBLN, 2014). gbXML and IFC file formats were used for data exchange between the architectural BIM model and the energy analysis software.

For the test suite, the architectural model of a two-story detached house was taken as a sample. In addition to the geometry it contains supplementary information, such as building construction elements, space objects, schedules and a simple ventilation system.

Interoperability with the gbXML file format was tested with Green Building Studio, the SketchUp plugin for Energy Plus, and the Ecotect Analysis simulation tools. The FZK-viewer checking tool was employed (Karlsruhe Institute of Technology, 2014) to verify and validate the content of the exported gbXML model.

Then the exchange of data was examined using the IFC file format. The simulation tools that support import from an IFC file are Ecotect Analysis and IFC-compatible user interfaces for EnergyPlus, i.e. SBT and Simergy. Graphisoft ArchiCAD and Solibri Model Checker (SMC) were used (Solibri, 2014) to check the consistency and completeness of the content exported from the Revit IFC file.

6.2 *Geometry*

Typically, the three-dimensional digital models of building are generated for purposes other than the simulation of energy performance, e.g. as an architectural or visual representation of the building. However, such models do not meet the required quality for application in the context of building energy simulation. It is a major challenge to adjust the originally modeled geometry and other data of the building for use with simulation software (Maile, 2013).

The incorrect or inconsistent calculation of volume is another reason for false simulation results. For example, when calculating the volume of space, a suspended ceiling or false floor must be considered for correct volume values and subtracted from the total gross volume. It is therefore essential that spatial boundaries are properly defined. Similarly, results vary depending on whether the highest surface of the building is the ceiling of the top floor or the roof itself (Cemesova et al., 2013).

Spatial boundaries are of great importance for the energy performance simulation. If the components and spaces are not defined correctly, the spatial boundaries cannot be determined. And where elements have complicated geometries, e.g. freeform shapes or changing wall thickness, spatial boundaries are not calculated or are calculated incorrectly. This can result in gaps in the spatial boundaries in the geometry transfer using the gbXML format (see Osello et al., 2011).

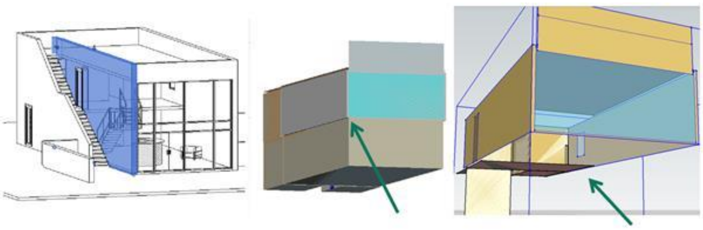

Figure 4. Transformation flow of the geometry from BIM model to SketchUp Plugin for EnergyPlus simulation engine. The arrows point to the displacements and absence of original elements.

6.3 *Material properties*

Energy simulation tools that support the import of IFC or gbXML format, define default values for the material properties of imported geometric objects. The use of these default values cannot always be attributed to limitations in the file formats that represent and store all relevant material properties; they are just not yet fully exploited by export or import mechanisms in the corresponding architectural or BEPS software, as these programs lack a means by which to enter these properties into the exported building model (see Hitchcock & Wong, 2011).

To implement data exchange using third-party applications, an open data schema is required to export the material properties data. In the context of Autodesk Revit, IFC or gbXML can be used. The values of thermal conductivity, density and specific heat capacity in the exported IFC file were set by the software to zero according to validation with SMC. Despite the fact that the IFC data scheme has options to provide such information (for example, an object for thermal conductivity IfcThermalConductivityMeasure according to BuildingSMART, 2013c), the data is not transferred. Autodesk Revit is able to export the building model as a gbXML file. The test revealed that Revit does not write complete building data from its own internal model to gbXML format, so material properties are not included in the exported gbXML file.

The file formats IFC and gbXML, which contain a building information model, already comprise information on the material properties and constructions. The lack of support of automated import functions for material properties represents an obstacle to the utilization of these possibilities. A further difficulty is the lack of export functions for material data from Autodesk Revit 2013 to the gbXML format. Currently, this has to be entered manually in software for building energy simulation as does the assignment of material properties for the imported architectural and geometric objects within their user interface.

6.4 *Building systems*

The simulation tool we tested, Ecotect Analysis, cannot manually perform the handover of TGA information to the IFC format. The data can only be entered in a rudimentary manner within the Ecotect user interface. The description of technical building systems is limited to the type of system, system efficiency and desired temperature range.

The lack of a flexible and versatile means of defining technical building systems and components provides a barrier to the exchange of data in EnergyPlus simulation engine. There is a gap in the transformation of the IFC file to the input data for EnergyPlus, which is difficult to overcome because of the complexity of building systems. A relatively simple but limited solution is the use of available templates for building systems in EnergyPlus (see Hitchcock & Wong, 2011).

So far, only IFC-compliant tools can create detailed information on TGA systems, among them Simergy which can create HVAC information, and read and write it to and from the IFC file (Bazjanac & Maile, 2004). Simergy is the only simulation tool in the entire test suite that declares and implements an exchange of HVAC components using the IFC file format. In this case, the transfer within Simergy employs its own method called SimModel, which is used as a translation scheme from BIM objects to objects in the EnergyPlus model.

6.5 *Site conditions*

The open formats gbXML and IFC for building data models have the ability to store the geographical coordinates of the building location and its orientation with respect to the cardinal points. The orientation is normally transmitted together with the geometry data of building components. Building models do not contain any actual information on weather conditions, such as temperature, solar radiation, wind direction, etc. This climate data and weather conditions are derived from geographic coordinates read from external data sources, including the internet.

Although location data can be exported and stored, the inability of the simulation tools to read such information from the BIM model file is disadvantageous. For example, when importing both exchange formats into the Ecotect Analysis simulation tool, the location is reset to the default city of New York and there is no data exchange.

6.6 *Building operation information*

The operation information depends on the usage type of building and the behavior of users; it is therefore difficult to capture and describe with sufficient accuracy during the building design phase.. In simulation tools this type of data is not directly extracted from a building model, but consists of pre-assumed datasets for certain usage types of buildings. The building usage type is definable in the building model (gbXML or IFC formats) or can be entered manually in the simulation software.

The operating conditions of the building, schedules, and internal loads can be selected in Revit from predefined variants. Revit’s internal simulation plugin, GBS, has good interoperability with the internal building model in Revit with regard to operating conditions. However, data exchange with external programs in this data field is only poorly supported. Both variants of the open data formats, gbXML and IFC, include no details of the operation information of the building after export from Revit. Futhermore, testing the import a gbXML file with predefined operation data into Ecotect revealed that it did not detect the data. The software tool defines a default value for the number of people, internal heat sources, etc., or requires manual input, instead of using the data from the gbXML file.

6.7 *Results and summary*

The results of the test suite are summarized in table 1. Although geometry data is the most important data for building simulation, it is only one part of the ideal data flow and integration of BIM and BEPS. Green Building Studio has a good data exchange capability with the proprietary building information model in Revit, but it is a closed Autodesk-specific solution with limited options for building energy simulation.

Table 1. Results of the test suite.

Software / Data	EnergyPlus SBT	EnergyPlus SketchUp	Symergy (EnergyPlus engine)	Ecotect Analysis	Green Building Studio
Geometry	+	+	+	+	+
Material Properties	+/-	-	-	-	++
Building Systems	-	-	+	-	-
Building Operation Information	-	-	-	-	++
Building Systems	-	-	-	-	++

Not (-), partly (+/-), imperfect (+), and fully (++) implemented.

7 CONCLUSIONS

Currently, the seamless data import of building geometry data into energy simulation tools has its limitations and involves a process of prior modification of the architectural model and post manual checking and fixing of partially transformed geometries. In our tests, we were able to illustrate the problems of geometry conversion using an example model. A difficult prerequisite for performing energy simulations are the space boundaries and the spatial limits and interrelations of room objects. The creation of space boundaries is the most common challenge for software implementations where building geometries are more complex.

Energy simulation tools are usually used during the planning phase. In the early phases of the design, we found the solution from Autodesk for GBS especially helpful. The more isolated application from Revit to GBS has a higher degree of interoperability between BIM and BEPS. The method uses solid body geometry which, compared with the building element geometry used by other solutions, makes the creation of a thermal model more reliable and suitable for decision-making in the conceptual building design.

The use of the geometry of the architectural model for energy simulation in the later planning phases and subsequent phases as part of the building's lifecycle is hampered by the often complex geometrical definitions, though the BIM approach is intended to be used in all stages of building development.

Despite the fact that geometry data is the most important data for building simulation, it is only one part of the ideal data flow between BIM and BEPS. The gbXML schema provides the functionality for the exchange of simplified building geometry for simulation, material properties, some HVAC information, and data about usage and location of the building. The IFC model contains more detailed and comprehensive definitions across all disciplines and lifecycle phases.

For reliable data exchange, however, export and import functionality needs to be fully implemented in the respective software tools and also thoroughly tested. The existing tools for building energy simulation have data import functionality from architectural BIM software, but it is only fully implemented for three-dimensional geometry and component objects. Additional information, such as the thermodynamic properties of building materials, systems for building services and so on, is not or only partially exchanged. Since, for the most part, only geometry data is stored or imported, the data modelling capabilities of gbXML and IFC formats are not used to full capacity.

8 FUTURE WORK

Further work will examine the potential to make the exchange of data between the domains of BIM and building energy performance simulation more widely applicable and the simulation process more intuitive. The interoperability increase within the scope of the BIM approach makes BIM itself more attractive and flexible for business (Osello et al., 2011). To be able to successfully perform building energy simulation, it is therefore necessary to promote data exchange between BIM and simulation programs.

Standards need to be developed for verifying the quality of building models for the purpose of building energy simulation. Existing tools provide the ability to verify and validate; they also can be used to improve the quality of building models and thereby reduce the number of errors significantly. For a faster response, model checking should be (more fully) implemented as part of the model export functionality of architectural software.

In addition, the low conversion quality of the geometry of building models must be improved. The export and import functions of the geometry data need to be made more precise and frequently recurring errors fixed either automatically or at least detected earlier. Improvements to software, together with a better training of the people who create models, would significantly help to improve the reliability of the use of BIM models for energy simulation.

The software currently available on the market does not utilize all the possibilities contained within the IFC and gbXML formats, and it is necessary to improve their export and import functions. This applies equally to software tools used for generating the architecture as well as for energy performance simulation. Further developments to this interoperability requires a high degree of standardization of data exchange processes. An example of this could be the introduction of a new certification process (Certification 2.0) for the IFC format (Smart Building, 2013B). This certification intends to bring about a significant improvement in the quality of data exchange. The use of the new version of IFC, IFC4, which contains improvements to the building geometry (spatial boundaries), will also help promote the exchange of data.

A reliable and properly implemented data exchange process is essential to assist in optimal decision-making for the sustainable design of buildings and tofacilitating the design, construction and operation of energy-efficient buildings.

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