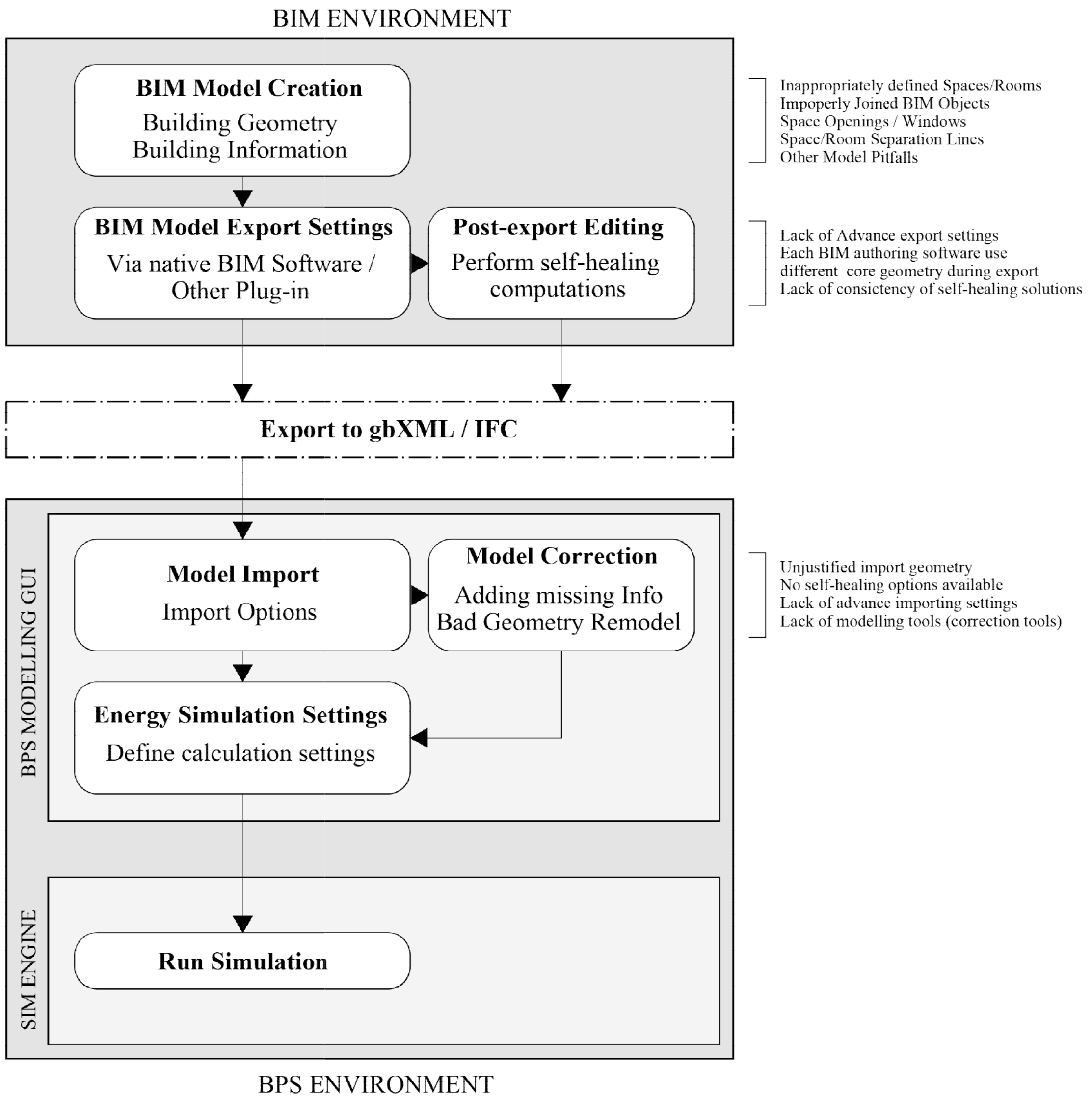
A 4.3.3 STATE OF THE ART ANALYSIS ON BIM AND NUMERICAL SIMULATION INTEROPERABILITY

Date:	18/01/2021
Prepared by:	PP3 CI-EEWRC - BEN ISPC-CNR
Status:	Final
Version:	V 06
Authors:	Kristis Alexandrou, Georgios Artopoulos (PP3 CI-EEWRC) - Elena Gigliarelli, Filippo Calcerano, Letizia Martinelli (BEN ISPC-CNR)

This project is funded by the EU under the ENI CBC Med Programme

Abstract

This document is part of the Activity 4.3.3: ''State of the Art analysis on BIM and numerical simulation Interoperability''. The purpose of this document is to explore and address the current state of BIM to BPS Interoperability development, its reasoning, challenges and current workflow approaches in AEC daily practice. It seeks to provide critical insights of the current obstacles the AEC industry is facing regarding this activity, in order to allow the Project partners to select and implement the most efficient semi-automatic workflow available. A brief introduction and a schematic representation of the problem formulation is documented in Section 2. The current level of BIM and BPS integration, BIM and BPS information requirements and the importance of an effective BIM to BPS conversion is described in Section 3. Interoperability and data exchange schemas of IFC and gbXML are presented in Section 4. Existing solutions available in practice are offered in Section 5, while Section 6 concludes with the limitations of the exchange process and a description of future research.



Schematic representation of BIM to BPS Interoperability problem

Index

1. INTRODUCTION

3.1 Background

The building sector is responsible for contributing up to 30% of the global greenhouse gas emissions (GHG) and for consuming almost 40% of the total energy production. The implementation of Energy Efficiency (EE) in the built environment is one of the principal objective of the European Union's (EU) action plan for sustainable development (EBPD 2010). For restraining the energy consumption and environmental footprint of the building stock, EU and various International institutions formulated a series of policies and regulations, which lead to the establishment of new standards around energy rehabilitation strategies and the promotion of smart technology solutions (see BEEP Output 3.1 § 2.2, AA. VV. 2020). In addition, these directives set a new reference point for energy performance requirements and consequently bring forward the concept of nearly zero energy buildings (nZEB). The realization of Energy Efficiency objectives within tight financial budgets and durable result expectations stress the need for advanced control over the life cycle costs (LLC) of buildings (Liu, Xianhai, and Chiming 2015). The impact of design decision on the energy and environmental performance of a building is much higher as these decision are closer to the early design stages (Lechner 1991). Under these lines, the early involvement of MEP engineer, the need for early energy-related insights as well as the continuous monitoring of the buildings' energy performance responses are becoming essential key aspects for the entire building planning and asset management process.

The tight interrelation of these objectives points out the importance of a well-formulated approach of rapid deployment, which requires collectiveness and collaboration among the involved professionals. The necessity for shifting over to a renewed, integrated planning practice is commonly considered as a step forward to better deal with cost-effective energy saving developments (Ryan and Sanquist 2012).

In the last decade, Building Information Modelling (BIM), defined as the use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions (ISO 19650-1 2018), became a popular approach which encapsulates the above capacity for sustainable building development. BIM puts in place all the necessary tools for activating an integrated design and planning workflow. This is accomplished through the embodiment of building information within the geometrical model itself. Hence, a native BIM software acts as a core database of information of multiple dimensions, classifying the building's operational, financial, managerial, ecological and maintenance attributes and functions. However, exporting BIM data for Building Performance Simulation (BPS) applications depends on data exchange formats and their subsequent file standards compatibility. When information is fully defined and appropriately registered, a single export can save a significant amount of time, effort and potential error occurrences, as compared to reproducing the respective Energy Model in a native BPS environment (Pinheiro et al. 2016).

The transferring of information between BIM and BPS software is carried out under Open BIM standards, through the data exchange schema (DES) of Industry foundation Class (IFC) or Green Building eXtensible Markup Language (gbXML) (Augenbroe 2002; Pinheiro et al. 2016; Kamel and Memari 2019). Amongst the majority of BPS software packages, gbXML is considered a more straight forward option for use with many BPS software packages, since the schema output is lighter in size and dedicated to energy-related information exchange (for a comparison of the two file formats see §3.10). However, despite the potential of BIM technology for generating a collective and automated design and planning workflow, the interoperability of BIM to BPS is yet not fully functional nor effortless (Rahmani Asl et al. 2015; Kamel and Memari 2019; Hijazi, Kensek, and Konis 2015; E. Gigliarelli et al. 2019). An exported BIM model may result into decomposed or unjustifiably interpreted geometry, with numerous incidences of improper or inadequate data conversion.

3.2 Glossary

AEC	*Architecture, Engineering and Construction*
BCF	*BIM Collaboration Framework*
BI-EM	*Building Information-Energy Model. A BIM-based energy model that automates the energy modelling process within the BIM software (Revit Energy Model)*
BIM	*Building Information Modelling*
BIM-BPS	*Building Information Model to Building Energy Model. A converted energy model using exported information from a BIM model*
BPS	*Building Performance Simulation*
bSDD	*buildingSMART Data Dictionaries*
CFD	*Computational Fluid Dynamic*
DTV	*Design Transfer View*
DES	*Date Exchange Schema*
FM	*Facility Management*
GBS	*Green Building Studio*
gbXML	*Green Building eXtensible Markup Language*
HVAC	*Heating, Ventilation and Air Conditioning*
IAI	*International Alliance for Interoperability*
IDM	*Information Delivery Manual*
IFD	*International Framework for Dictionaries*
IFC	*Industry Foundation Class*
ISO	*International Organization for Standardization*
LCC	*Life cycle costs*
MEP	*Mechanical, Electrical, and Plumbing*
MVD	*Model View Definitions*
Plenum	*A plenum is a non-occupiable space between a ceiling and the floor above specifically intended for mechanical systems and other systems that require ceiling space*
R-value	*Thermal Resistance*
RV	*Reference View*
SHGC	*A value describing the solar heat gain coefficient in a glazing (window) material*
Space	*A space is defined as a building volume enclosed by ceilings, floor, walls or by another space's boundary. Space has a plethora of properties assigned to it to describe its energy resources, such as loads from people, lighting and equipment*
U-value	*Heat Transfer coefficient or Thermal Transmittance*
Weather File (epw)	*A single file in a format called an .epw that contains a collection of information to describe the environment of a location for each hour*

	of the year, supplying data such as temperatures, luminescence data for sunlight, heating, and more
XML	*eXtensible Markup Language*
XSD	*XML Schema Definition*

3.3 Document Purpose

This document is part of the Activity 4.3.3. ''State of the Art analysis on BIM and numerical simulation Interoperability''. The purpose of this document is to explore and address the current state of BIM to BPS Interoperability development, its causes, challenges and current workflow approaches in AEC daily practice. It seeks to provide critical insights of the current obstacles the AEC industry is facing around this subject, in order to allow the Project partners to select and implement the most efficient semi-automatic workflow available.

A brief introduction and a schematic representation of the problem formulation is documented in Section 2. The current level of BIM and BPS integration, BIM and BPS information requirements and the importance of an effective BIM to BPS conversion is described in Section 3. Interoperability and data exchange schemas of IFC and gbXML are presented in Section 4. Currently available solutions are offered in Section 5, while Section 6 concludes with the exchange process limitations and future research description.

3.4 Project Scope

The studied BEEP research component is a subject belonging to multiple Engineering fields and disciplines. For the purposes of BEEP Project, the scope of this document is outlined in the table below:

In scope of this Document	Out of scope of this document
- Describe the problem formulation - Literature review of existing BIM to BPS workflows/conversions - Comparison of IFC and gbXML data schema - Provide guidance for an effective BIM to BPS Interoperability - Provide advice on establishing a successful semi-automatic workflow - Provide advice on avoiding/reducing parallel modelling between the two software environments	- Provide advice on IT solution - Provide software or scripts - Suggest the use of specific software packages or versions - Explain Energy Simulation Models

Table 1: Document scope

2. SCHEMATIC REPRESENTATION OF PROBLEM

As stated in the introduction, the need of the AEC industry to engage in a more collaborative design and planning practice is commonly considered as a great development for enhancing the final resolution (richness and accuracy) of a building outcome in all its critical aspects. BIM technology provides a complete digital solution for modelling, storing, editing and managing building information, while promoting a clear role designation to the involved professionals. During a project's development, the engagement of project engineers with numerical simulations at different project phases, is of primary importance. For this reason, BIM authoring software should be able to exchange model information seamlessly. From research literature and professional practice reports, the interaction of the two is still away from being smooth and error-less (Rahmani Asl et al. 2015; Kamel and Memari 2019; GSA 2015; Hijazi, Kensek, and Konis 2015).

Currently, AEC firms rely on a plethora of design and simulation software, when it comes to explicit tools and services for project collaboration. Communication and interoperability between these tools depend on data exchange formats and their compatibility (Augenbroe 2002), which within the BIM pipeline is typically ensured by a Common Data Environment (CDE). A CDE represents the agreed source (and repository) for collecting, managing and disseminating information for any given project (ISO 19650-1 2018). It aligns the process of model collaboration with the established industry collaboration protocols to enable multiple users to perform collaboration operations on model content management, content creation, viewing and reporting and system administration. In particular, the exchange of digital models should be filtered in order to map only the segment of data that is essential for the particular numerical simulation, i.e., in the case of BPS, simplified building geometry and thermal data. Currently, project files exported from BIM software are usually too condensed in information and too large in size for the basic needs of simulation software to operate correctly. Therefore, project professionals are often called to manually remodel and reregister the information before executing the building numerical simulation. This lack of compatibility leads to increased time-consuming processes which are also prone to human error, inconsistencies and redundancies, especially in large construction projects, with multiple planning and design phases. Approximately 80% of the total resources needed to perform a building simulation are consumed on unnecessary replicating actions (Ryan and Sanquist 2012).

Despite the aforementioned workflow obstacles found in process of the model data transfer from BIM to numerical simulation software, in the case of BIM to BPS conversion, the level of complexity becomes even higher. Contrary to a native BIM model, BPS input data are much more abstract

, in terms of the building's geometrical input as well as of the alphanumerical information. Therefore, the transfer of information from BIM to BPS demands serious simplification of the building geometry from 3D objects to 2D surfaces. For this reason, the exporting process is also subjected to geometric computational conversion processes, also known as 'healing computations'. Current efforts occupied with the BIM to BPS interoperability issue utilise both the IFC and gbXML data schemas. Specifically, a schematic representation of the interoperability problem is presented in Figure 1.

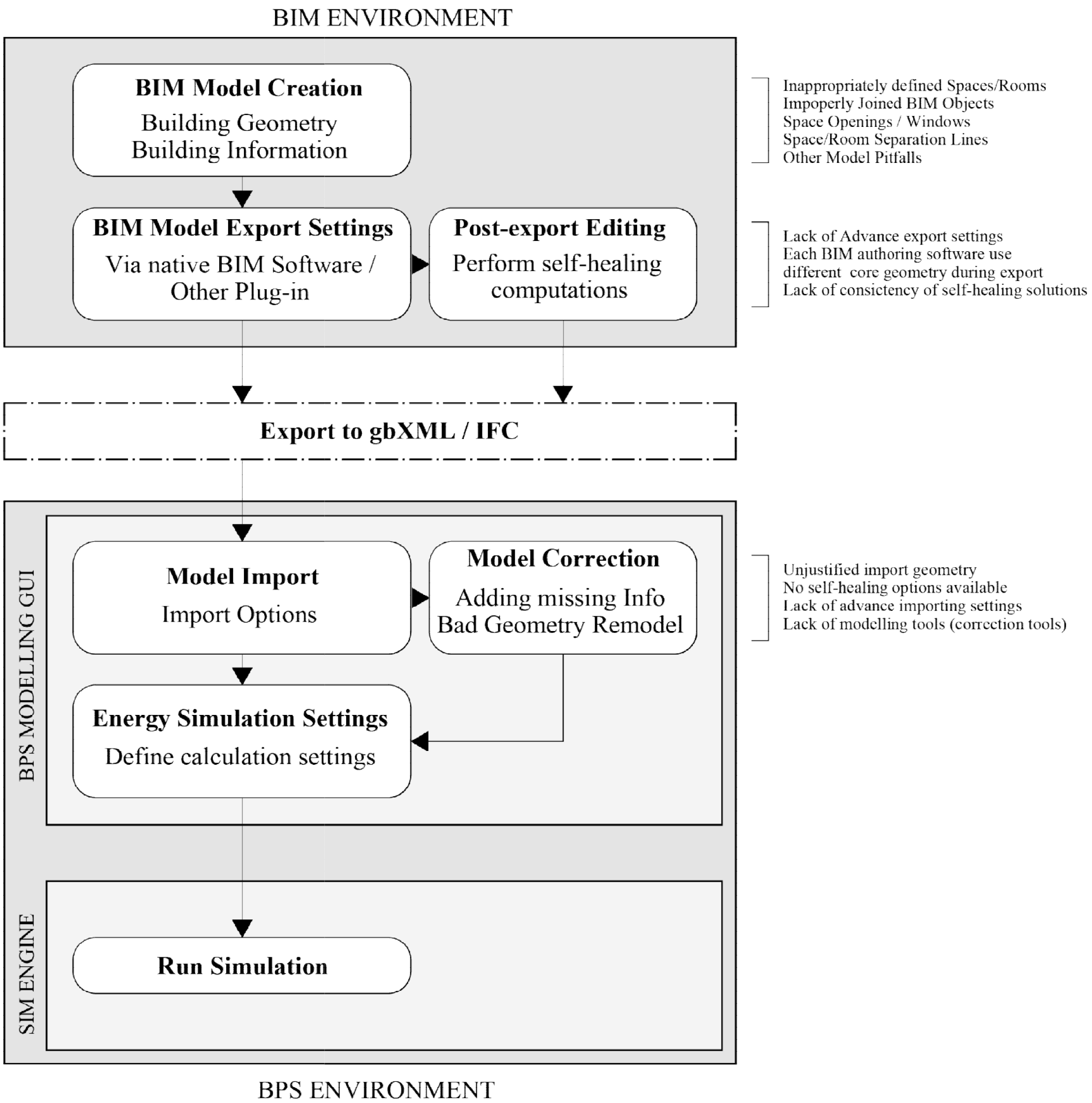


Figure 1: Schematic representation of BIM to BPS Interoperability problem

3. BIM FOR BPS

3.5 Building Information Modelling

A Building Information Model refers to the digital model of a building that contains a wide spectrum of information from a variety of construction industry fields. This model includes input from all construction stakeholders, including the architect, structural engineer, mechanical engineer, energy engineer, and others, that defines building attributes from the beginning of its lifecycle until its demolition (Sacks et al. 2018). According to literature, the majority of BIM definitions refer to the model as a series of actions of broad changes in design, construction and facility management, instead of a digital object in itself. In particular, BIM is described as a set of policies, processes and technologies, which set the standards for a holistic collaborative methodology for building design and construction (Succar 2009). BIM technology is described as one of the most promising developments happening in the AEC industry which enables and integrate design and construction workflow.

3.1.1 BIM maturity levels

The level of implementation of BIM technology depends on the level of complexity of a building Project but more importantly on how the model will be used (Jayasena and Weddikkara 2013). For scalability reasons, this characteristic is formally described as BIM maturity. In short, the level of maturity defines the level of collaboration between industry professionals. In Figure 2 the schema of BIM maturity levels developed by the BIM Industry Working Group is presented (BIM Industry working group (BIWG) 2011). The diagram was developed for the British Government Construction Client Group and is rapidly adopted throughout Europe. These levels are formulated based on industry standards of the disciplines involved.

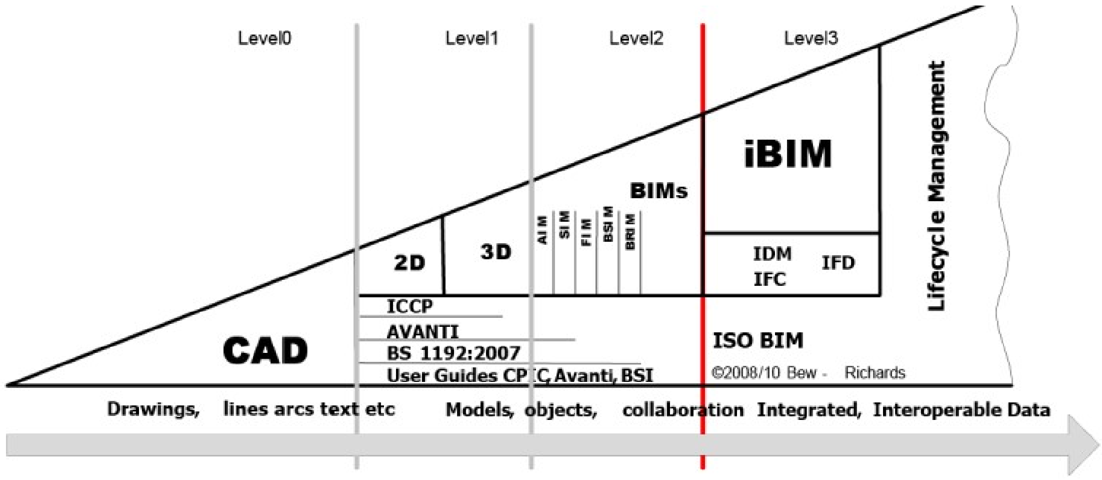


Figure 2: Maturity scheme – BIM Industry Working Group (BIM Industry working group (BIWG) 2011).

The implementation of a BIM model at maturity level 3 means that all previous levels' requirements are fully respected and realised. At level 0, only CAD drawings and spreadsheet calculations are executed. This level includes no digital models and is commonly referred to as the document-oriented level. Level 1 is the first step towards a basic BIM model. At this stage, a 3D model of the building is developed, however, it still cannot be used for cost, operations or other calculations. This option can be achieved at maturity level 2, where building information is assigned to the building objects. At final stage 3, building information is shared between the involved professional through open BIM standards. Level 3 provides a full utilisation of BIM technology and ideally sets the standards for a seamless collaboration.

Facilitating a frequent and structured collaboration between the involved parties is boosted at BIM maturity levels 2 and 3. Consequently, the interoperability between native BIM software and other numerical simulation packages becomes critical. A seamless exchange of information between the two software environments may accelerate the building development workflow or even enable automation.

3.1.2 Level of Development (LOD) and Level of information Need

Another important aspect of BIM implementation is the definition of the level of information, both geometrical and alphanumerical, within a BIM model and its elements. A very common term to express this concept is the Level of Development (LOD). This term is used to describe both the geometrical and alphanumerical level of information incorporated in a model for each and every modelling phase of a project's development (Boton, Kubicki, and Halin 2015). Level of Development is divided in a scale of 5 levels, namely, in the US version, L100, L200, L300, L400 & L500 (Choi, Kim, and Kim 2015). L100 represents the level of information of a conceptual design, whereas, L500 indicates a geometry at an as-built level, with information reaching the operation and maintenance level. Similarly to level of maturity, the decision of LOD for a BIM model is directly related to its purpose and uses.

ISO 19650 (2018) introduces the corresponding concept of Level of Information Need, that defines the extent and granularity of information to be provided to satisfy the information related purposes of each model element. Compared to LOD, it stressed the importance of the "right" amount of information to be delivered, to avoid redundancy and waste (Churcher and Davidson 2019). Moreover, it is intended as a general framework to be adapted to the specific BIM process, without providing a strict template, but leaving a lot of flexibility to implementation; therefore, it is well suited for interoperability workflows, that require ad-hoc solutions.

When it comes to BIM for BPS interoperability, Level of information Need becomes probably the most important aspect for consideration, in avoiding convergence issues (Sacks et al. 2018). While a L500 (that could correspond to a specifically defined, very high Level of Information Need) model creates the best conditions for the ultimate control and management of a construction project when a very high detail is required, it makes things difficult for the energy professionals involved. Due to the fact that BPS environment support only simplified geometry of single surfaces for each room/space face, a L500 BIM model carries unnecessary information for the former. In geometrically heavy models, the establishment of a proper and automated conversion/simplification of the geometry is constantly at risk. Although the data schema of gbXML may manage better the transition of only energy-related alphanumerical information, the conversion/simplification of the model geometry remains an unsolved process of the export workflow; for a comparison of approaches see (Guzmán Garcia and Zhu 2015; Dong et al. 2007; Lam et al. 2012; Hijazi, Kensek, and Konis 2015; Garwood et al. 2018; Pinheiro et al. 2016).

3.6 Building Performance Simulation (BPS)

The design of the built environment is a complex task involving the interaction among technical domains, diverse performance expectations and emerging uncertainties. Building Performance Simulations provide a means to deal with these complexities allowing the exploration of design solutions and their impacts (Clarke and Hensen 2015), mainly in terms of environmental and energy performance. Despite the impact of strategic decisions on the energy and environmental characteristics of a building is much higher when these decisions are close to the early design stages (Lechner 1991), BPS are mainly used as a performance confirmation at later stages of design instead of a design support through the whole design process starting from the early design stages (Morbitzer 2003; Bambardekar and Poerschke 2009). While the implementation of Energy and Environmental Simulation at a later stage of the design process will impact only the few design parameters that are still flexible (Morbitzer 2003), resolving usually in a fine tuning of the HVAC systems, and having a less meaningful impact upon the quality of the building design, an early energy simulation engagement will instead affect the design trajectory, in terms of the building's shape, form and size (Morbitzer 2003). Therefore, to design high performance buildings it is important to assure informed decision making during the early design phases and this also includes the use of BPS tools (Attia et al. 2012). BPS can also contribute positively during the building's operation stage, by determining the optimum operational schedule of the HVAC systems, dynamic shading systems and other technical services. An effective utilisation of BPS can achieve an optimum balance between cost, comfort and energy efficiency.

3.3.1 The importance of an effective BIM to BPS interoperability

The sustainable development of a building project requires an iterative energy analysis that starts from conceptual design phase to the detailing and finally the operation stages. This iterative process, enhanced by the BIM technology advantages, may enable reaching the full potential of sustainable building design (Pinheiro et al. 2016). An effective BIM to BPS interoperability solution can enable the following advantages:

- Time saving for unnecessary remodelling processes and reduce error-prone manual re-input of data.
- Facilitate energy engineers perform energy simulations using the updated version of the model at every design or operation phase of the project.
- Automatically implement changes of the model between phase A and B.
- Take advantage of BIM parametric modelling tools to test new design ideas or perform optimization techniques based on energy-related criteria, in a short amount of time.
- Bridge the gap between BIM professionals and energy engineers, by providing energy analysis feedback back into BIM model.

3.3.2 BPS Information Requirements

Figure 3 provides an overview of the input data necessary to perform an Energy analysis. Input data differ in case of a static or a dynamic simulation. The classification of data is based on the four following categories: Environmental Data, Building Data, Occupants Data, Heating & cooling loads and Building service systems & operational schedules. The scope of this section is to provide a basic understanding of the level of information needed to be registered in a BIM model before exchanging with BPS software. For BEEP project, all necessary BPS information requirements are described in *A.3.2.5 Environmental and Energy analyses*.

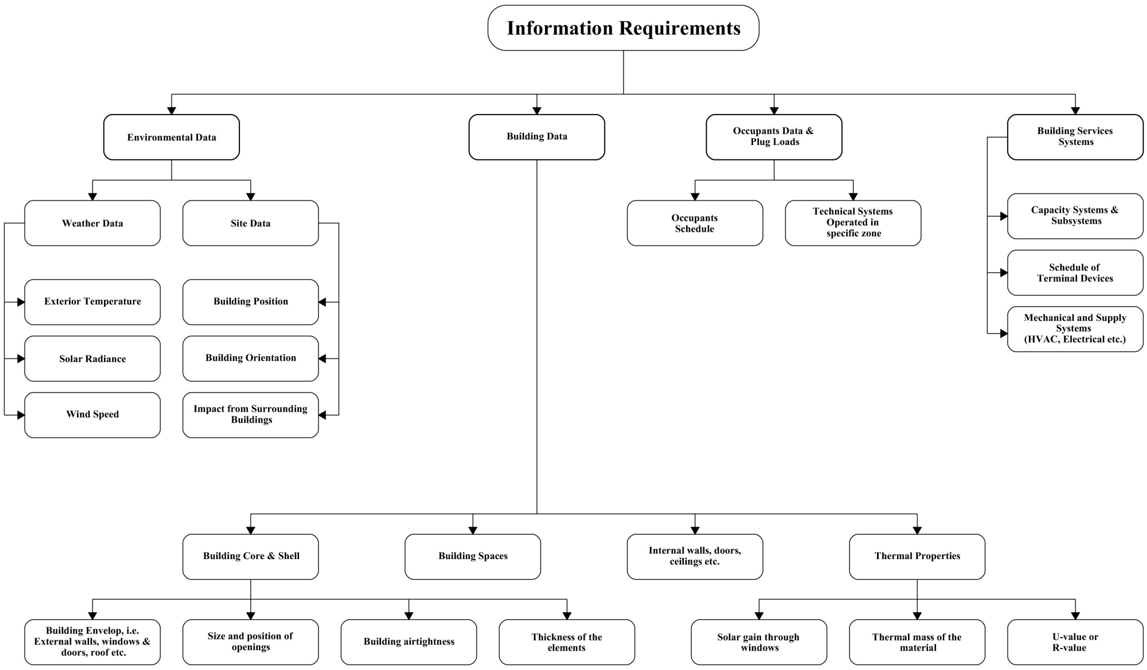


Figure 3: BPS Information Requirements (Karlapudi 2018).

4. INTEROPERABILITY AND DATA EXCHANGE SCHEMAS

3.7 Interoperability

The term interoperability is used here to describe the process of data sharing or exchange between a BIM software and a numerical simulation software, in order to remove the need for data model regeneration (Sacks et al. 2018). According to literature, one of the biggest obstacles in solving current interoperability misfunctioning and enabling the wider adoption of BIM-based energy analysis is the data exchange between the BIM and BPS models (Costa and Madrazo 2015). The problems generally arise from the different logic with which the two software environments evolved (Hijazi, Kensek, and Konis 2015; E. Gigliarelli et al. 2019), which reduced the possibility for simulation software to exploit the potential offered by object-oriented programming of BIM software (Abanda, Vidalakis, and Tah 2015; Jeong et al. 2014). The difficulties in a seamless conversion of BIM-based data into coherent BPS-model depend on simplifications and assumptions required for making the energy simulation models (Ahn et al. 2014), and the relative need to convert/transform data in the process. The lack of a standardised process in building energy modelling (E. Gigliarelli et al. 2017; Hitchcock and Wong 2011; Guruz, Katranuschkov, and Scherer 2016) and the gap still present between design and energy modelling are the main limitations that impede the process (Wilkins and Kiviniemi 2008). The transfer of both geometric and informative data between software is still imprecise (Lam et al. 2012; Pinheiro et al. 2016) and requires a strong supervision/manual intervention, thus reducing the main benefits of an exchange process that is as automated as possible. Another typical problem occurs when modelling strategies optimised for other model uses, i.e., architectural or structural optimisation, are in conflict and do not allow an orderly division of the objects modelled for exchanges between disciplines, as it usually occurs between Architectural, Structural and MEP BIM (Tchouanguem Djuedja et al. 2019). A seamless exchange of data between the two (BIM software and a numerical simulation software) heavily depends on the proper filtering of the data, i.e., eliminate redundancy and maintain a simplified exchange process.

3.4.1 Open Standard Exchange Schemas

Software interoperability between BIM and other simulation software is achieved through digital format exchange using common proprietary or open standards. The following open and neutral file exchange formats are currently being used to enable interoperability between BIM and BPS:

IFC: Industry Foundation Class

This is a global standard file format mostly used for solving interoperability between different native BIM software. IFC is designed to store information of geometry, including its respective classification, properties and quantities.

gbXML: Green building eXtensible Markup Language

This industry supported file format is tailored to make the exchange of information from a CAD-based BIM environment to a BEM environment. gbXML is dedicated to store element attributes that are dominantly energy related.

Each data schema has its own advantages and disadvantages when it comes to BIM for BPS conversion. In literature there are many comparisons of the above exchange languages (Hijazi, Kensek, and Konis 2015; Lam et al. 2012; Pinheiro et al. 2016; Dong et al. 2007), however, errors still occur irrespective of the file format that is used (Kamel and Memari 2019). Manual adjustments are still necessary to resolve incorrect or improper conversion/translation or storing of the information. In order to improve interoperability, the developers of IFC and gbXML continue to work on updates of the exchange schemas. However, the lack of knowledge about different native BIM software is considered a major obstacle for reaching and providing a solid interoperability solution to the market today (NBS 2014; 2015), and the same is true also for the lack of knowledge about different BPS software and their heterogeneity in addressing the simulation tasks (input data needed, approach etc.). Currently, there many research efforts on providing native BIM plug-in tool for model correction or stand-alone post export editing tool for solving the interoperability problem. More information about current solutions is provided in Section 5.

3.8 Industry Foundation Class (IFC)

IFC[1] is an open meta-data schema used to transfer building information from one software to another among all professionals of a design, construction and facility management project. IFC is developed by buildingSMART and its formulation is based on open International standards. The purpose of buildingSMART is to deliver a good quality data exchange schema in order to match the information needs of the entire building industry, hence IFC include terms, concepts and specifications from the involved disciplines. IFC has been structured in a four conceptual layer, Resource layer, Core layer, Interoperability layer and domain layer (Figure 4) with a total of approximately 800 entity definitions, thousands of data attributes and much more standardised object properties.

Resource Layer: is the lowest layer in the IFC data schema architecture and provides commonly used resources. It can be used or referred by classes in the other layers.

Core Layer: consists the elementary structure of the IFC and defines most abstract generic concepts. Further dedicated input is handled by the following layers of the IFC object model.

Interoperability Layer: This is specialized information added to core layer objects. This info is shared among multiple model domains.

Domain Layer: layer responsible for additional information to model objects that will be used by domain experts.

[1] For more information see https://technical.buildingsmart.org/standards/ifc/

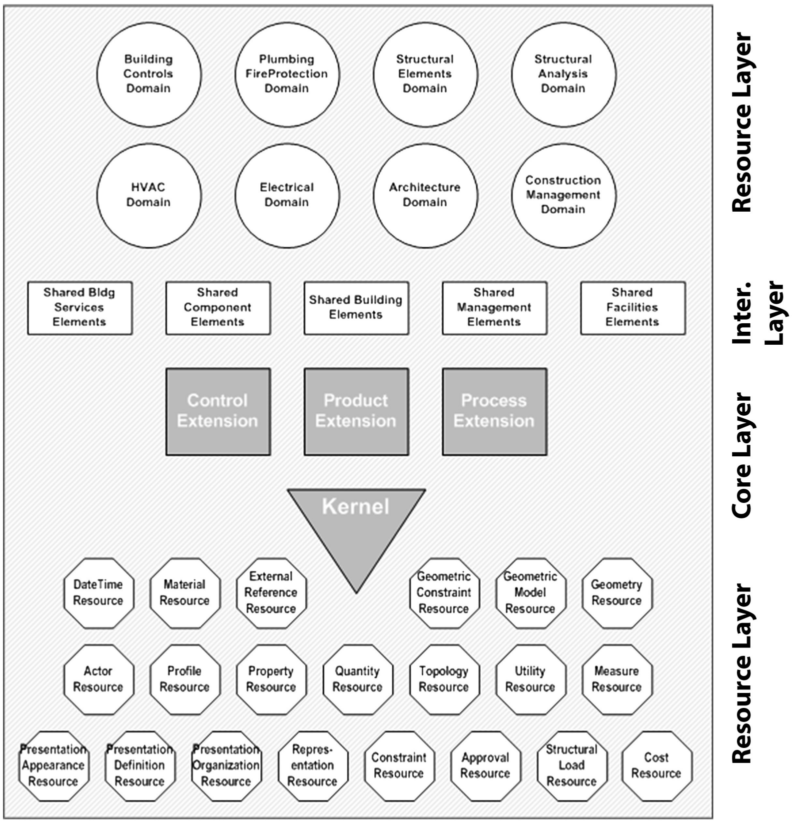


Figure 4: IFC Data schema with four conceptual layers (buidingSMART 2020).

The official latest IFC version currently in use is IFC4.1, released in 2018 (buidingSMART 2020). Compare to its previous versions, IFC4.1 can define a model at higher level of detail. In the context of building energy analysis, IFC 4.x can describe different building boundaries and store additional HVAC information. Extensions made to the IFC4.1 schema include:

- Description of alignment as a combination of horizontal and vertical alignment;
- Linear Placement according to ISO 19148;
- IfcSectionedSolidHorizontal as a new geometry representation particular useful for describing infrastructure facilities.

3.9 Green building eXtensible Markup Language (gbXML)

The gbXML[2] schema is developed by Green Building Studio (GBS) in 1999. The schema stores data in the form of eXtensible Markup Language (XML) language, turning it into machine and human readable language. XML enables users to modify the language and thus, it allows for customization on data domain exchange. Specifically, its use and purpose can be greatly differing according to its semantic structuring. gbXML facilitates the exchange of explicit building information, such as weather data, building geometry, HVAC systems, lighting and thermal zones, thermal loads, schedules, etc., making it more appropriate for supporting interoperability between BIM native software and engineering tools (Ham and Golparvar-Fard 2015a). The gbXML schema is rich in data and can store up to 500 types of building elements and attributes. Each building

[2] For more information see https://www.gbxml.org/About_GreenBuildingXML_gbXML

component, from architectural to MEP model, holds its own information and has its own reference ID. The following figure shows the hierarchy of information organisation of the schema (Figure 5).

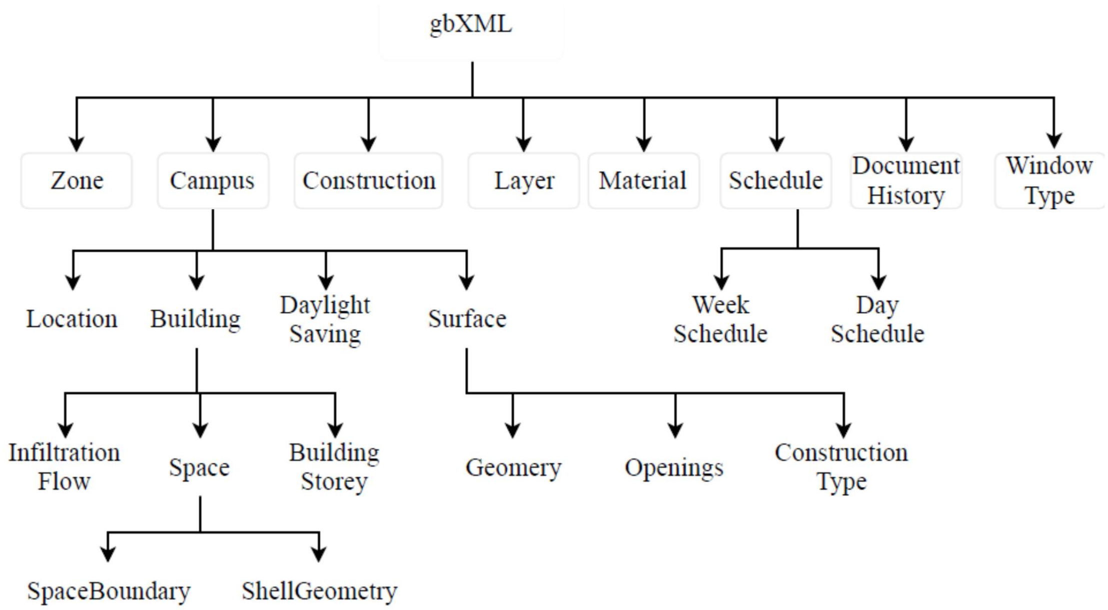


Figure 5: Simplified hierarchy of information organisation in gbXML schema (Ham and Golparvar-Fard 2015).

The concept of reference ID is to form necessary relationships between other components. For example, a wall, roof or slab component is defined as surface, which in turn defines the geometry, construction information and information about the opening on that surface. The construction information includes all wall layers; within each layer it stores the material and thermal information separately and linked to the construction type. The details of the type on opening are linked to the actual components using reference ID.

The primary ''Building'' component of gbXML defines the building, including information of the different storey levels, which further defines space types included in it. The ''Space'' component is assembled by ''Room binding elements'', such as wall, roof, floor etc. Bounding elements consist of two nodes, ''Shell Geometry'' and ''Space Boundary''. Shell Geometry defines the inner surface of the adjacent wall, while space boundary defines the coordinates of the centreline of the Bounding Element. In case of an internal wall, which is separated by two consecutively located spaces, the centreline and both faces of the wall are defined. ''Operating schedule'' and ''Occupants' schedule'' are defined separately and linked to the space thought the reference ID mechanism.

3.10 Data exchange schemas comparison

Data exchange schemas are constantly under development and they are increasing their added-value on dealing with interoperability improvement. This is acknowledged by many researchers, i.e., (Guzmán Garcia and Zhu 2015; Ham and Golparvar-Fard 2015b; Cemesova, Hopfe, and Mcleod 2015; Cheng and Das 2014). Each schema carries its own advantages and drawbacks. According to Moon et al. 2011, the gbXML schema is more dedicated to BIM for BPS exchange operations, officially supported by many BIM software providers. However, the IFC schema is more developed data model for buildings in the AEC industry, able to transfer all building information data (Sacks et al. 2018). In this context, IFC may provide an interoperability solution for all types of numerical simulation interoperability needs. In the case of BIM to BPS however, IFC causes time consuming simulation runs or even software crashes. gbXML on the other hand may be more compact and more popular in the AEC industry, although still it does not allow to perform a complex geometry exchange between a native BIM software and a BPS. This is because the gbXML schema can only accept rectangular planar shapes. Compared to the ''top-down'' approach of the IFC, the gbXML employs a ''bottom-up'' process, which makes it more accessible and flexible to handle.

3.11 Conversion from BIM to BPS

Currently, the conversion of a BIM model to a BPS model could be achieved in a fully automated, semi-automated or non-automated (manual) fashion.

- The fully-automated concept refers to the idea of automatically and instantly generating a fully-defined BPS model from a BIM model. This idea is currently being promoted by Autodesk seeking to create a fully-automated BIM to BPS exchange between *Revit* and *Green building studio*, via gbXML exchange schema. Today, this approach can be applied only in the case of small-scale buildings of conventional rectangular shape, and in any case it does not take into consideration the need of the energy modeller to design his own simulation by making simplifications or modifications compared to the starting BIM model (such as for example for the definition of thermal zones).
- The semi-automatic concept refers to the idea of exporting only the necessary (and/or possible to transfer) data from a BIM model, i.e., building geometry, spaces, material thermal properties, etc. The exported file is then imported into third party BPS software to further execute the simulation. Depending on the complexity of the export BIM model, additional modelling or information registration work in the BPS software may be necessary.
- The non-automatic, or manual conversion, process is the case that is usually being followed today by the energy modelling industry. In this case the user is required to remodel the building in the BPS modelling environment before running the analysis.

3.12 The 'H' factor in BIM to BPS Interoperability

Heritage buildings add an extra layer of complexity in both geometry and information data implementation. This complexity adds extra difficulty to the issues that stem from the application of the energy simulation methods to historical buildings (A.4.3.2 paragraph 2.3), partly because of data transfer/exchange. Regarding the geometric aspects, the process for converting geometry from walls with thicknesses in the BIM environment to the two-dimensional surfaces of the walls in the energy model (BPS) is challenged by the particularities of built heritage. Specifically, historic buildings frequently have walls with variable thickness, floor height changes (E. Gigliarelli et al. 2019), while they typically feature complex geometric shapes, such as vaults or domes, that cannot be easily modelled in BIM and then converted into the energy model.

Moreover, heritage buildings usually necessitate additional consideration on the way their thermophysical behaviour and the relation between surfaces can be adequately represented in the energy model. In the representation of a historic building envelope, even the transfer of information data can encounter specific problems, as it is substantially dependent on the heterogeneity of the layers and the properties of the materials (also due to variable patterns of decay on the same type of wall), as well as the considerable lack of standardisation. There do exist solutions towards the right direction, which usually need extension to fit the specificities of heritage buildings, for example, the COBie Information Delivery Manual (IDM) for historical buildings[3].

4 INTERNATIONAL GUIDELINES

Even though the topic of BIM and BEM interoperability is still in its infancy, research has started more than ten years ago. The following table lists the documents which attempt to systematise this transfer of data, highlighting the critical aspects of both the process and operation:

Table 1: International Guidelines

Title	Author-year	Main Topics covered
GUIDELINES for OptEEmAL BIM Input Files.	(Giannakis et al. 2019)	The guidelines develop a IFC BIM-based building energy model generation methodology to streamline the process and reduce errors. The BIM authoring tool investigated is Autodesk Revit, and the consortium also produced a dedicated IFC exporter.
Project Execution Planning guide, version 1.2.	(Computer Integrated Construction Research Group, PENN State University 2019)	The guide contains a flowchart for BIM-based energy analyses highlighting the information exchanges and the stakeholders involved.
A study of national BIM guidelines from around the world determining what future Swedish national BIM guidelines should contain.	(Kralsson and Rönndahl 2018)	A comparative study of BIM guidelines from ten countries (Australia, Belgium, Canada, Finland, Hong Kong, New Zeland, Norway, Singapore, UK and US), containing an appendix on the simulation and energy analysis.

[3] https://technical.buildingsmart.org/standards/information-delivery-manual/idm-database/

IBPSA Project 1 - BIM/GIS and Modelica Framework for building and community energy system design and operation.	(IBPSA 2017)	The project focuses on the creation of new computational tools based on Modelica to build the basis of the next generation computing tools focusing on open standards IFC and CityGML.
EDSL Guide for Revit gbXML Files	(Cadline 2016)	The guide focuses on the creation of a useable Revit model for gbXML exporting for EDSL TAS Engineering simulation software.
BIM Guide 05 Energy Performance, version 2.1	(GSA 2015)	The guide aims at helping the US General Service Administration in the development of their BIM execution plans, also taking into account the energy modelling. The guide contains insights on the role of BIM within the energy modelling process and case studies.
RP-1468 -- DEVELOPMENT OF A REFERENCE BUILDING INFORMATION MODEL (BIM) FOR THERMAL MODEL COMPLIANCE TESTING	(Clayton et al. 2013)	The report contains guidelines for mapping a Revit BIM model into a description (the most relevant subset of information) for energy modelling in DOE-2 simulation software.
Task 2.2.12 – CMU Report 02: Identification and Analysis of Interoperability Gaps between Nbims/Open Standards and Building Performance Simulation Tools.	(Lam et al. 2012)	The report focuses on interoperability gaps between IFC and gbXML open standards and energy modelling. IFC and gbXML are also compared.
HESMOS - Deliverable D2.1: BIM Enhancement Specification	(Liebich et al. 2011)	The project developed an Information Exchange Requirement for an Information Delivery Manual for a BIM to simulation process.
Implementation guide:	(Weise et al. 2011)	The guide is addressed to

space boundaries for energy analysis		software developers for supporting the exporting of space boundaries in IFC format also tackling the issue of the specific Model View Definition.
Information Delivery Manual (IDM) for BIM Based Energy Analysis as part of the Concept Design BIM 2010.	(Weise et al. 2011)	The guide addresses the data flow between BIM and simulation workflows, stressing the need for energy analyses from the conceptual design phase.
An automated IFC-based workflow for building energy performance simulation with Modelica	(Andriamamonjy, Saelens, and Klein 2018)	This paper describes the essential elements of this an integrated workflow, achieved with the already available technology, Information Delivery Manual (IDM) and a newly developed Model View Definition. This MVD is tailored to the needs of Building Energy Performance Simulation (BEPS) that uses the Modelica language together with a specific library (IDEAS) and can easily be adapted to other libraries.

For a selection of recent European Research Projects on BIM to BPS interoperability please refer to (AA. VV. 2020, para. 6.2)

5 LIMITATIONS & ONGOING RESEARCH

5.1 Limitations

The principal obstacles in the conversion process from BIM to BPS environment lie mainly in the quality of data, already existing in the BIM model as well as the exporting data schema translation. These limitations cause the following issues:

- Inadequate or fragmented spaces and thermal zones;
- Missing (mainly lost during the improper translation) or additional (result for example of an incorrect translation of the three-dimensional envelope into surfaces) building components;
- Wrongly placed walls and openings;
- Misinterpreted wall to wall or wall to window joint conditions
- Wrong boundary conditions
- Wrong conversion of informative data.

These errors are generated mainly due to the modelling process followed in the native BIM software, in conjunction with the inability of the exchange schemas to interpret the geometry in a solid and comprehensible manner. Another contributing aspect to the complications above is the immense level of data currently incorporated in a BIM model, such as furniture, architectural ornaments, mechanical systems, electrical and plumbing objects, etc.

5.2 Ongoing Research

The joint application of BIM and numerical simulations of building energy performance on historic buildings (i.e., Energy Efficient Heritage BIM) is still not widespread in professional practices. Even the conversion of BIM or the application of energy simulation to the case of heritage constructions, entails additional methodological considerations[4]. The application of these methodologies to historic buildings aims at maximising the potential offered by new technologies. The application of Energy Efficient Heritage BIM constitutes a complex variant (E. Gigliarelli et al. 2017; 2019) of the studies that currently address the issue of interoperability between BIM and simulations in the case of new constructions (Senave and Boeykens 2015; Maile et al. 2013; GSA 2015; Kamel and Memari 2019). One of the most significant case study in terms of joint use of the two technologies can be found in the Italian industrial research project METRICS Management and Requalification of Historic Centres and Buildings, funded by the PON Research and Competitiveness 2007-2013 (Gigliarelli, Calcerano, and Cessari 2017). The objective of METRICS was the development of innovative approaches and methodologies for the energy improvement of historic centres. The project addressed the issue with a multiscale, multidisciplinary and holistic approach, which involved the use of HBIM technology as a basis for the environmental energy analysis of buildings and the development of intervention strategies both on the urban scale and on the individual building. Among other objectives, this project focused on the interoperability between HBIM and dynamic simulations software ecologies (E. Gigliarelli et al. 2017; 2019) (Elena Gigliarelli et al. 2017; E. Gigliarelli et al. 2019).

[4] For more information see chapter 4 and par 5.3 of (AA. VV. 2020)

6 REFERENCES

AA. VV. 2020. 'A3.1.1 STATE OF THE ART ANALYSIS ON HBIM AND INTEROPERABILITY - ENICBCMed BEEP Project'.

Abanda, F H, A H Oti Vidalakis, and J H M Tah. 2015. 'A Critical Analysis of Building Information Modelling Systems Used in Construction Projects'. *Advances in Engineering Software* 90: 183–201. https://doi.org/10.1016/j.advengsoft.2015.08.009.

Ahn, Ki-Uhn, Young-Jin Kim, Cheol-Soo Park, Inhan Kim, and Keonho Lee. 2014. 'BIM Interface for Full vs. Semi-Automated Building Energy Simulation'. *Energy and Buildings*, The 2nd International Conference on Building Energy and Environment (COBEE), 2012, University of Colorado at Boulder, USA, 68, Part B (January): 671–78. https://doi.org/10.1016/j.enbuild.2013.08.063.

Andriamamonjy, Ando, Dirk Saelens, and Ralf Klein. 2018. 'An Automated IFC-Based Workflow for Building Energy Performance Simulation with Modelica'. *Automation in Construction* 91 (July): 166–81. https://doi.org/10.1016/j.autcon.2018.03.019.

Attia, Shady, Elisabeth Gratia, André De Herde, and Jan L. M. Hensen. 2012. 'Simulation-Based Decision Support Tool for Early Stages of Zero-Energy Building Design'. *Energy and Buildings* 49 (June): 2–15. https://doi.org/10.1016/j.enbuild.2012.01.028.

Augenbroe, Godfried. 2002. 'Trends in Building Simulation'. *Building and Environment* 37 (8–9): 891–902. https://doi.org/10.1016/S0360-1323(02)00041-0.

Bambardekar, Suhas, and Ute Poerschke. 2009. 'The Architect as Performer of Energy Simulation in the Early Design Stage.' *Proceedings of Building Simulation 2001: 1st Conference of International Building Performance Simulation Association, Glasgow, Scotland, July 27-30,2009*.

BIM Industry working group (BIWG). 2011. 'A Report for the Government Construction Client Group Building Information Modelling (BIM) Working Party Strategy Paper, Available on-Line at Http://Www. Bimtaskgroup. Org/Wp-Content/Uploads/2012/03'. URN 11. Innovation and Skills. Department of Business.

Boton, Conrad, Sylvain Kubicki, and Gilles Halin. 2015. 'The Challenge of Level of Development in 4D/BIM Simulation Across AEC Project Lifecyle. A Case Study'. *Procedia Engineering* 123: 59–67. https://doi.org/10.1016/j.proeng.2015.10.058.

buidingSMART. 2020. 'Industry Foundation Classes 4.0.2.1 - Reference View 1.2'. BuildingSMART. https://standards.buildingsmart.org/MVD/RELEASE/IFC4/ADD2_TC1/RV1_2/HTML/.

Cadline. 2016. 'EDSL Guide for Revit GbXML Files'.

Cemesova, Alexandra, Christina J. Hopfe, and Robert S. Mcleod. 2015. 'PassivBIM: Enhancing Interoperability between BIM and Low Energy Design Software'.

Automation in Construction 57 (September): 17–32. https://doi.org/10.1016/j.autcon.2015.04.014.

Cheng, Jack C P, and Moumita Das. 2014. ‘A BIM-Based Web Service Framework for Green Building Energy Simulation and Code Checking’. *Journal of Information Technology in Construction* 19: 150–68.

Choi, Jungsik, Hansaem Kim, and Inhan Kim. 2015. ‘Open BIM-Based Quantity Take-off System for Schematic Estimation of Building Frame in Early Design Stage’. *Journal of Computational Design and Engineering* 2 (1): 16–25. https://doi.org/10.1016/j.jcde.2014.11.002.

Churcher, David, and Sarah Davidson, eds. 2019. ‘Information Management According to BS EN ISO 19650 - Guidance Part 1: Concepts’. UK BIM Alliance.

Clarke, J. A., and J. L. M. Hensen. 2015. ‘Integrated Building Performance Simulation: Progress, Prospects and Requirements’. *Building and Environment*, Fifty Year Anniversary for Building and Environment, 91 (September): 294–306. https://doi.org/10.1016/j.buildenv.2015.04.002.

Clayton, M, J. Haberl, W. Yan, S. Kota, F. Farias, W. Jeong, J. Kim, and J.L.B. Alcocer. 2013. ‘RP-1468 -- DEVELOPMENT OF A REFERENCE BUILDING INFORMATION MODEL (BIM) FOR THERMAL MODEL COMPLIANCE TESTING’.

‘Collaboration and Interoperability’. 2018. In *BIM Handbook*, by Rafael Sacks, Charles Eastman, Ghang Lee, and Paul Teicholz, 85–129. Hoboken, New Jersey: John Wiley & Sons, Inc. https://doi.org/10.1002/9781119287568.ch3.

Computer Integrated Construction Research Group, PENN State University. 2019. ‘Project Execution Planning Guide’. https://www.bim.psu.edu/bim_pep_guide/.

Costa, G, and L Madrazo. 2015. ‘Connecting Building Component Catalogues with BIM Models Using Semantic Technologies: An Application for Precast Concrete Components’, 10.

Dong, B., K. P. Lam, Y. C. Huang, and G. M. Dobbs. 2007. ‘A Comparative Study of the IFC and GbXML Informational Infrastructures for Data Exchange in Computational Design Support Environments’. In *Proceedings: Building Simulation 2007*.

EBPD. 2010. ‘Directive 2010/31/EU of the European Parliament and the Council of 19 May 2010 on the Energy Performance of Buildings’. *Official Journal of the European Union*, 12–35.

‘Facilitators of BIM Adoption and Implementation’. 2018. In *BIM Handbook*, by Rafael Sacks, Charles Eastman, Ghang Lee, and Paul Teicholz, 2018th ed., 323–63. Hoboken, New Jersey: John Wiley & Sons, Inc. https://doi.org/10.1002/9781119287568.ch8.

Garwood, Tom Lloyd, Ben Richard Hughes, Dominic O’Connor, John K. Calautit, Michael R. Oates, and Thomas Hodgson. 2018. ‘A Framework for Producing GbXML Building Geometry from Point Clouds for Accurate and Efficient Building Energy Modelling’. *Applied Energy* 224 (August): 527–37. https://doi.org/10.1016/j.apenergy.2018.04.046.

Giannakis, G I, K Katsigarakis, G N Lilis, and S Álvarez-Díaz. 2019. 'GUIDELINES for OptEEmAL BIM Input Files', 18.

Gigliarelli, E., F. Calcerano, M. Calvano, F. Ruperto, M. Sacco, and L. Cessari. 2017. 'Integrated Numerical Analysis and Building Information Modeling for Cultural Heritage'. In *Proceedings of 3rd IBPSA Italy Conference 8-11 February, BSA 2017, Bozen/Bolzano, Italy*. Bolzano.

Gigliarelli, E., F. Calcerano, F. D'Uffizi, C. Di Biccari, G. Mangialardi, and M. Campari. 2019. 'From Heritage BIM to BPS, a Computational Design-Based Interoperability Approach'. In *Building Simulation 2019, Rome*. Rome.

Gigliarelli, Elena, Filippo Calcerano, and Luciano Cessari. 2017. 'Heritage Bim, Numerical Simulation and Decision Support Systems: An Integrated Approach for Historical Buildings Retrofit'. *Energy Procedia*, Climamed 2017 – Mediterranean Conference of HVAC Historical buildings retrofit in the Mediterranean area 12-13 May 2017 - Matera, Italy, 133 (October): 135–44. https://doi.org/10.1016/j.egypro.2017.09.379.

GSA. 2015. 'BIM Guide 05 Energy Performance'. U.S. General Services Administration.

Guruz, R., P. Katranuschkov, and R. J. Scherer. 2016. 'EeBIM LAB – TOWARDS A COHERENT GREEN BUILDING DESIGN PROCESS'. In *Proceedings of Central European Symposium on Building Physics CESBP 2016 / BauSIM*. https://www.researchgate.net/publication/310450225_eeBIM_LAB_-_TOWARDS_A_COHERENT_GREEN_BUILDING_DESIGN_PROCESS.

Guzmán Garcia, Elizabeth, and Zhenhua Zhu. 2015. 'Interoperability from Building Design to Building Energy Modeling'. *Journal of Building Engineering* 1 (March): 33–41. https://doi.org/10.1016/j.jobe.2015.03.001.

Ham, Youngjib, and Mani Golparvar-Fard. 2015a. 'Mapping Actual Thermal Properties to Building Elements in GbXML-Based BIM for Reliable Building Energy Performance Modeling'. *Automation in Construction* 49 (January): 214–24. https://doi.org/10.1016/j.autcon.2014.07.009.

———. 2015b. 'Mapping Actual Thermal Properties to Building Elements in GbXML-Based BIM for Reliable Building Energy Performance Modeling'. *Automation in Construction*, 30th ISARC Special Issue, 49 (January): 214–24. https://doi.org/10.1016/j.autcon.2014.07.009.

Hijazi, Mohammad, Karen Kensek, and Kyle Konis. 2015. 'Bridging the Gap: Supporting Data Transparency from BIM to BEM'. In *ARCC 2015 Conference – The FUTURE of Architectural Research (Chicago, IL)*, 8.

Hitchcock, R. J., and J. Wong. 2011. 'Transforming Ifc Architectural View Bims for Energy Simulation'. *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November*.

IBPSA. 2017. 'IBPSA Project 1 - BIM/GIS and Modelica Framework for Building and Community Energy System Design and Operation'. 2022 2017. https://ibpsa.github.io/project1/index.html.

ISO 19650-1. 2018. *ISO 19650-1:2018 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information*

Modelling (BIM) — Information Management Using Building Information Modelling — Part 1: Concepts and Principles.

Jayasena, Himal Suranga, and Chitra Weddikkara. 2013. ‘ASSESSING THE BIM MATURITY IN A BIM INFANT INDUSTRY’. *Sri Lanka*, 8.

Jeong, WoonSeong, Jong Bum Kim, Mark J. Clayton, Jeff S. Haberl, and Wei Yan. 2014. ‘Translating Building Information Modeling to Building Energy Modeling Using Model View Definition’. *The Scientific World Journal* 2014. https://doi.org/10.1155/2014/638276.

Kamel, Ehsan, and Ali M. Memari. 2019. ‘Review of BIM’s Application in Energy Simulation: Tools, Issues, and Solutions’. *Automation in Construction* 97 (January): 164–80. https://doi.org/10.1016/j.autcon.2018.11.008.

Karlapudi, Janakiram. 2018. ‘A Methodology to Classify and Determine Data Sharing Requirements between OpenBIM Models and Energy Simulation Models’. In , 112.

Kralsson, I. T., and C. Rönndahl. 2018. ‘A Study of National BIM Guidelines from around the World Determining What Future Swedish National BIM Guidelines Ought to Contain’. Bachelor Thesis, Jönköping University - School of Engineering. https://bimalliance.se/library/4352/isak-karlsson-christoffer-roenndahl.pdf.

Lam, K. P., O. Karaguzel, R. Zhang, and J. Zhao. 2012. ‘Identification and Analysis of Interoperability Gaps between Nbims/Open Standards and Building Performance Simulation Tools’. Task 2.2.12 – CMU Report 02: Center for Building Performance and Diagnostics. http://www.andrew.cmu.edu/user/okaraguz/TechnicalWritingSamples/Interoperability_Identification.pdf.

Lechner, Norbert. 1991. *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*. Hoboken, N.J.: John Wiley & Sons.

Liebich, T., K. Stuhlmacher, P. Katranuschkov, R. Guruz, N. Nisbet, J. Kaiser, B. Hensel, R. Zellner, T. Laine, and M.-C. Geißler. 2011. ‘HESMOS Deliverable D2.1: BIM Enhancement Specification’,. http://e2b.ectp.org/fileadmin/user_upload/documents/E2B/HESMOS/HESMOS_WP02_D02_1__Final.pdf.

Liu, Sha, Meng Xianhai, and Tam Chiming. 2015. ‘Building Information Modeling Based Building Design Optimization for Sustainability’. *Energy and Buildings* 105: 139–53. https://doi.org/10.1016/j.enbuild.2015.06.037.

Maile, T., J. O’Donnell, V. Bazjanac, and C. Rose. 2013. ‘BIM-Geometry Modelling Guidelines for Building Energy Performance Simulation’. *Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28*.

Moon, Hyeun Jun, Min Seok Choi, Sa Kyum Kim, and Seung Ho Ryu. 2011. ‘Case Studies for the Evaluation of Interoperability between a BIM Based Architectural Model and Building Performance Analysis Programs’. In *Proceedings of 12th Conference of International Building Performance Simulation Association*, 12:p326-328.

Morbitzer, C. 2003. ‘Towards the Integration of Simulation in the Building Design Process’. Strathclyde: PHD thesis, Energy System Research Unit, University of Strathcylde.

NBS. 2014. ‘NBS National BIM Report 2014’. https://www.thenbs.com/knowledge/nbs-national-bim-report-2014.

———. 2015. ‘NBS National BIM Report 2015’. https://www.thenbs.com/knowledge/nbs-national-bim-report-2015.

Pinheiro, Sergio, J Donnell, Reinhard Wimmer, Vladimir Bazjanac, S Muhic, Tobias Maile, Jérôme Frisch, and Christoph Treeck. 2016. ‘Model View Definition for Advanced Building Energy Performance Simulation’. In .

Rahmani Asl, Mohammad, Saied Zarrinmehr, Michael Bergin, and Wei Yan. 2015. ‘BPOpt: A Framework for BIM-Based Performance Optimization’. *Energy and Buildings* 108 (December): 401–12. https://doi.org/10.1016/j.enbuild.2015.09.011.

Ryan, Emily M., and Thomas F. Sanquist. 2012. ‘Validation of Building Energy Modeling Tools under Idealized and Realistic Conditions’. *Energy and Buildings* 47 (April): 375–82. https://doi.org/10.1016/j.enbuild.2011.12.020.

Sacks, Rafael, Charles Eastman, Ghang Lee, and Paul Teicholz. 2018. ‘Introduction’. In *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*, Third Edition, 1–31. John Wiley & Sons.

Senave, M., and S. Boeykens. 2015. ‘Link between BIM and Energy Simulation’. *WIT Transactions on The Built Environment, Vol 149, © 2015 WIT Press*. https://doi.org/10.2495/BIM150291.

Succar, Bilal. 2009. ‘Building Information Modelling Framework: A Research and Delivery Foundation for Industry Stakeholders’. *Automation in Construction*, 357–75. https://doi.org/0.1016/j.autcon.2008.10.003.

Tchouanguem Djuedja, Justine Flore, Mohamed Hedi Karray, Bernard Kamsu Foguem, Camille Magniont, and Fonbeyin Henry Abanda. 2019. ‘Interoperability Challenges in Building Information Modelling (BIM)’. In *Enterprise Interoperability VIII*, edited by Keith Popplewell, Klaus-Dieter Thoben, Thomas Knothe, and Raúl Poler, 9:275–82. Proceedings of the I-ESA Conferences. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-13693-2_23.

Weise, M., T. Liebich, R. See, V. Bazjanac, T Laine, and B. Welle. 2011. ‘Implementation Guide: Space Boundaries for Energy Analysis’.

Wilkins, Chris, and Arto Kiviniemi. 2008. ‘Engineering-Centric BIM’. *ASHRAE Journal December 2008*.