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EXTENDING CAPABILITIES OF BIM TO SUPPORT PERFORMANCE BASED DESIGN

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SUMMARY: As we advance towards high-performance buildings, it is becoming necessary to reinforce and extend the role of building information modelling (BIM) to better support performance-based design. To achieve an optimally functioning building that fulfils the need of the end-user and is designed in an environmentally conscious manner necessitates considering energy performance, environmental performance, indoor air quality, lighting, and acoustics. To consider these multiple criteria, use of computer-based modelling tools and comprehensive simulation methods becomes essential. These criteria are typically assessed after the main phases of architectural design of the building, and the knowledge is passed on to the engineers for development of the technical design. During the technical design process, the exchange of data between the design model and a selected building performance aspect may occur. This paper investigates the potential of BIM-based models at the core of providing input data required for performance-based simulations (BPS) to enable iterative multi-criteria assessment towards high performance buildings. A comprehensive literature review of 249 documents was conducted to identify the current state of knowledge and provide future directions for design and simulation tools to better quantify and evaluate the performance aspects. Furthermore, it explains and clarifies stakeholders' current ability, needs, barriers, and potentials in using BIM for assessing building performance through nineteen expert interviews of key BIM stakeholders in Finland.

KEYWORDS: BIM, Performance-based design, Energy performance, Environmental performance, Indoor air quality, Lighting, Acoustics.

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1. INTRODUCTION

As described by the International Organization for Standardization (ISO), the building performance requirement is the minimum acceptable level of a critical property (ISO 6707-1, 2014). Performance-based design can be defined as a process where the targeted solution is described with the help of its required performance (CIB Report publication 64, 1982). Kalay (1999) defines performance-based design as an approach focused on a holistic view where functions and aesthetics are not compromised and at the same time ensuring the ecological and environmental performance of a building. Lützkendorf et al. (2005) describe building performance as a major concept divided into categories: functional, technical, environmental, economic, social and process performance. According to Sexton and Barrett (2005) and Eriksson and Westerberg (2001), performance-based and qualitative requirements give the best basis for innovative design solutions.

Achieving an optimally functioning building that fulfils the need of the end-user necessitates identifying and quantifying the performance (Gursel *et al.*, 2009), setting measurable targets which can be monitored during different phases of design and implementation (Koskela, 2000), and considering multiple criteria. There have been many attempts to outline the overall building performance and describe various performance aspects with the help of indicators which can be used for requirement setting (Alwaer and Clements-Croome, 2010; Augenbroe and Park, 2005; Frandsen *et al.*, 2010; Loomans *et al.*, 2011; Prior and Sziget, 2003). Also, ISO (ISO 21929-1, 2011) presents indicators of a sustainable building with fourteen aspects, such as emissions to air, the consumption of non-renewable resources, indoor conditions (including lighting and acoustics) and air quality, etc. For example, a standard indicator of building energy efficiency is annual energy consumption (kWh/m²) as a function of climate, envelope design, heating ventilation and air-conditioning (HVAC) systems, and occupant behaviour, among other parameters (IEA ECBCS Annex 53, 2013). Similarly, for environmental performance, embodied impacts (e.g., greenhouse gas emissions) of a building are assessed based on life cycle data of building products. Indoor air quality includes assessment of the dynamics of gaseous and particulate pollutants and human exposure to these contaminants. Lighting of interior and exterior spaces in a building includes such factors as illuminance, luminance, daylight, and glare probability. Acoustical performance of indoor spaces is calculated based on reverberation time, sound intensity level, noise, and other factors that are important to be considered during design phases.

To achieve an optimally functioning building that fulfils the need of the end-user also necessitates assessing the building performance indicators with simulation methods by applying an iterative design process (Oduyemi and Okoroh, 2016). The simulation of different design aspects requires information from the design model such as that of quantities of products, performance characteristics of products, building elements and their surfaces, dimensions of spaces, etc. Iterative design towards required performance requires the availability of methods and tools that can be easily used by designers and that cover the selected performance criteria (Hopfe, 2009). The methods and tools used to carry out the assessment vary regarding complexity and accuracy, capacity, the quality of required input data, usability in different situations and phases of design, and validity. Negendhal (2015) categorized the method of integrating the design tools with BPS in three ways: (a) combined model method, which have simulation packages such as IESVE (IESVE, 2013), (b) central model method, which includes using shared data schema such as that of BIM, and (c) distributed model method where a middleware software is used to move data bi-directionally between building geometry model and BPS software. A major challenge in the application of simulation tools is how to deal with difficulties through a large variety of parameters and complexity of factors such as non-linearity, discreteness, and uncertainty (Hopfe and Hensen, 2011).

BIM-based models prepared by architects and designers (eg. structural, HVAC, mechanical electrical, plumbing) may have the potential to ease the management of input data significantly, to make BPS in different phases of design less time consuming, while considering performance criteria simultaneously. However, this may require that BIM-based and BPS-based methods are compatible to be deployed effectively along the design process to optimize multiple performance aspects in various phases of design. BIM as defined by the National Institute of Building Sciences (2016) is a digital representation of physical and functional characteristics of a facility. BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition (National Institute of Building Sciences, 2016). It contains interoperable information allowing it to be exchanged based on open standards, such as Industry Foundation Classes (IFC) widely used for data transfer.

The need, value, and usefulness of BIM is well established in the architectural, engineering and construction industry and facilities management (AEC/FM) and has been discussed by several studies. According to Yalcinkaya and Singh (2015) implementation and adoption of BIM has been the most important principal area in BIM research. However, when evaluating the need, value and usefulness of BIM, the AEC industry has focused on its potential to streamline the construction and delivery processes of a project. Past and current research trends have been riveted on studying the capability of BIM as a process management tool and its ability to help evaluate selected performance criteria as presented in section 3.1 and 3.2. This study investigates the potential of BIM-based models at the core of providing input data required for BPS to enable iterative multi-criteria assessment towards the future of high performance buildings. The specific objectives are:

- (1) To study the current capability and highlight the issues of data exchange between BIM-based and BPS-based tools/methods through a literature review.
- (2) To explain and clarify stakeholders' current ability, needs, barriers and potentials in using BIM-based models for assessing building performance through expert interviews.
- (3) Identify what kind of additional methods/procedures research (literature) and industry (expert interviews) calls for to ascertain building performance criteria.

1.1 Organisation of this study

The purpose of Section 1 (Introduction) is to position this study and explain the essential terms related to the scope of this study. Section 2 presents the method for the literature review (2.1) and the method used for the expert interviews (2.2). Section 3 is dedicated to the literature review of 249 documents organised in two parts, where 3.1 explains the generic benefits of using BIM and Section 3.2 links availability of BIM-based models to BPS methods for selected performance aspects. Section 4 is organized in two parts where, Section 4.1 discusses the qualitative results of the nineteen expert interviews, and Section 4.2 presents the quantitative results of the expert interviews. The qualitative results of expert interviews are designed in accordance with the architect's Plan of Work as presented in (Häkkinen *et al.*, 2015) and in this study structured as (i) Briefing, Preparation, Concept design, Developed design phases; (ii) Technical design and Construction phases; (iii) Building In-use and Warranty period phase. Section 5 is devoted to discussions focused on future need for performance-based design simulations using BIM-based models (Section 5.1) and Section 5.2 discusses the challenges in interoperability and information processes based on the literature review and the expert interviews followed by conclusions.

2. METHODS AND LIMITATIONS

2.1 Method for the literature review

A study of literature was conducted to summarise the current availability and capability of BIM compatible BPS tools and methods for designers and the scope of topics covered in the literature review are outlined in Figure 1. To fulfil objective 1, we concentrated on (1a) what information is needed as input variables to the simulation tools from the BIM model, (1b) can this information be brought from architects and designers' BIM model to the simulation model with the help of open standards such as Industry Foundation Classes (IFC). IFC is an international data exchange standard for building information developed by BuildingSMART formerly known as the International Alliance for Interoperability.

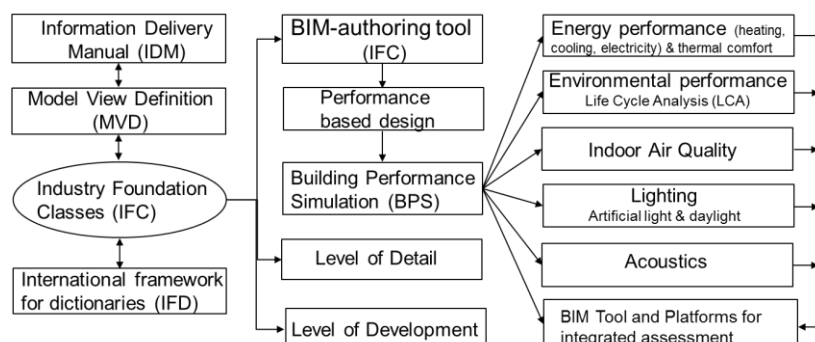


Figure 1. Scope of this study

There are different kinds of approaches for utilizing BIM for simulating building performance. This article focuses on approaches where the use of open standards such as IFC (ISO 16739, 2013) for data transfer is applicable. By BIM compatible tools, this study refers to widely used commercial tools/software that can exchange data via IFC. By ‘modelling’ this study relates to the creation and the authoring of the building information model in software such as Graphisoft ArchiCAD (ArchiCAD, 2017) and Autodesk Revit (Autodesk Revit, 2017) which are IFC compatible. This approach was selected because the open standard exchange enables any tool of any developer to utilise produced information but is restricted to the limited data properties of the standard. The limited data properties of IFC can be overcome by extending the property sets, to capture proprietary BIM content if agreed upon between the users. The resulting IFC exported files containing IFC objects with their properties can be used for sustainable building assessment (Fies, 2012). In addition, ISO 16739:2013 specifies a conceptual data schema and an exchange file format for BIM data (ISO 16739, 2013).

The building performance aspects assessed in this study are presented in section 3.2, and they were selected based on ISO standard 21929-1 Sustainability in building construction – sustainability indicators Part 1 (ISO 21929-1, 2011). Namely, five performance aspects studied comprise of energy performance (section 3.2.1); environmental performance (section 3.2.2); indoor air quality (section 3.2.3); lighting (section 3.2.4), and acoustics (section 3.2.5). Relevant articles based on title, abstract, and keywords (BIM, BIM compatible tools, performance, design, environment, energy, indoor air, acoustics, and lighting) were searched by using Scopus and Science Direct. During this process, a wide array of articles in specific journals were found. For the literature review, a total number of 249 documents were investigated including journal publications, conference publications, industry reports, scientific reports, standards, codes, factsheets, user manuals and thesis. Table 1 presents the subject of enquiry and the corresponding number of publications investigated in this study. It should be noted that each building performance aspect considered in this study is a scientific topic in itself. The focus of this study is not to dwell on the details of each performance aspect but on the potential to holistically assess the selected performance aspects. This can be ascertained by understanding capabilities of available BIM-based tools and BPS tools that can exchange data bi-directionally using open standards.

Table 1: Subject based enquiry and the corresponding list of publications investigated

Subject of enquiry	Number of publications investigated
Generic BIM	15
Performance Based Design (PBD)	18
IDM, MVD, IFC, IFD, Level of Detail, Level of Development	15
BIM tools and platforms for integrated assessment	13
Section 3.2.1 Energy performance assessment	32
(1) Required input data for building energy performance simulation	21
(2) No. of investigated tools/software for energy performance simulation	7
(3) Linking BIM-based data with BEP-based simulation	20
Section 3.2.2 Environmental performance	12
(1) Required input data for environmental performance assessment	3
(2) No. of investigated tools/software for environmental performance assessment	2
(3) Linking BIM-based data with environmental performance assessment	3
Section 3.2.3 Indoor Air Quality	9
(1) Required input data for IAQ simulation	5
(2) No. of investigated tools/software for indoor air quality simulation	2
(3) Linking BIM-based data with IAQ simulation (<i>not IFC based</i>)	3
Section 3.2.4 Lighting	7
(1) Required input data for lighting simulation	14
(2) No. of investigated tools/software for lighting simulation	4
(3) Linking BIM-based data with lighting simulations	14
Section 3.2.5 Acoustics	7
(1) Required input data for lighting simulation	16
(2) No. of investigated tools/software for acoustics simulation	4
(3) Linking BIM-based data with acoustics simulation	3
Total	249

Although the focus is on approaches that use open standards for data transfer, this study briefly mentions two other approaches where (1) the calculation algorithms are embedded in the BIM authoring software or the use of proprietary software-developer-specific file formats or even plug-in tools for design software (for example: (Liu *et al.*, 2015)) and (2) approach based on automatic bi-directional exchange of data, enabling designers to make parametric changes to the BIM-based model and simulate performance-based aspects simultaneously (for example: (Asl *et al.*, 2013)). As a limitation, the literature review focuses on the use of tools during the design process and does not deal with the usefulness of BIM in supporting the certification of sustainable buildings as that has been studied elsewhere, for example (Azhar *et al.*, 2011; Ilhan and Yaman, 2016; Wong and Zhou, 2015).

2.2 Method for the interviews

Expert interviews were conducted, to explain and clarify stakeholders' current ability, needs, barriers and potentials in using BIM for assessing building performance. During the discussions, we focused on what are the common practices for conducting simulations and pertaining problems as experienced by the interviewees and if the current simulation methods supports performance-based design (objective 2) and what is needed to improve the current practice (objective 3).

The basis of selection and identification of the expert interviewees for this study required that: (a) all the expert interviewees have more than ten years of experience in application and utilization of BIM in their domain as presented in Table 2. Other than this criterion, the experts were selected with no prior preference or bias of the authors. (b) The expert interviewees were identified by contacting engineering companies and architectural offices, while paying attention to actors that are members of the BuildingSMART Finland (2017). BuildingSMART Finland is a chapter under BuildingSMART International and a forum founded by Finnish AEC industry, large-scale property owners, and software vendors. This forum is meant for disseminating BIM related information and support implementation of BIM-based processes. (c) The authors requested Senate Properties (Senaatti-Kiinteistöt in Finnish) to list designers, architects, and BIM-coordinators that have been involved in their projects. Senate Properties is a government-owned enterprise and the largest building owner in Finland; their building portfolio consists of 9 300 buildings (Senaatti-kiinteistöt, 2017). Application of BIM is mandatory in all of Senate properties significant building projects that exceed the size of one million euro, making it a global forerunner in deploying IFC-based integrated BIM also noted by Gupta *et al.* (2014).

All expert interviews were conducted either face-to-face or by a teleconference between the interviewer and the interviewee. The duration of each interview lasted between 1-2 hours with nineteen respondents. To gain in-depth knowledge and enhance discussion, the interviews were semi-structured, so that the expert could add detailed background information or discuss the questions in addition to the questionnaire. A questionnaire was prepared and shared with the interviewees before conducting the interview. Each respondent was provided with a document of twelve open-ended and multiple-choice questions. During the interview, the importance of raised issues in the context of this study was assessed by all interviewees. Later, the interviewees were requested to further explain and reason their responses.

To capture the level of experience of the respondents, we asked them to explain their role in the design process based on their respective position in the company (see Table 2), their main motivation, and driver for exploiting BIM, and the most significant benefits of using BIM (see appendix 1 for the questionnaire). Table 2 lists the designation of the interviewees, role and features of the company in AEC industry to provide context to the readers. Consistent with extending the use of BIM in performance-based design, we asked the interviewees about: setting and monitoring of quantitative targets; the most important performance criteria that need or would need BIM compatible tools; the use of simulations tools available at present for building performance assessment; suitability of simulation tools in different phases of design; need for simultaneous consideration of various performance criteria; need for holistic design methodology; a comprehensive approach to support performance management; multi-criteria design and optimization of different performance criteria.

The limitation of our study include that the interviews were conducted solely in Finland. However, the outcomes of this study may have broader interest as Finland has been cited as one of the forerunners in the use of BIM (Finne, 2012; Rahman *et al.*, 2013; RIBA Enterprises Ltd, 2016). Additionally, the performance aspects and potential of BIM in performance-based design discussed in this study are of universal interest to the AEC/FM industry.

Table 2: List of Interviewees

	Designation in the company	Role of the company in AEC industry	Name and features of the company
1	Architect	Architectural design	Architects firm (In Finnish: Arkkitehtitoimisto) Lylykangas Kimmo
2	Architect	Architectural design	Architects (In Finnish: Arkkitehdit) Davidsson and Tarkela
3	Architect	Architectural design	Architects firm (In Finnish: Arkkitehtitoimisto) Lasse Kosunen
4	Architect	Architectural design	Architects firm (In Finnish: Arkkitehtitoimisto) Brunow and Maunula
5	Architect	Architectural design	JKMM Architects (In Finnish: Arkkitehdit)
6	Architect	Architectural design	L Architects (In Finnish: Arkkitehdit)
7	Architect	Architectural design	Parviainen Architects (In Finnish: Arkkitehdit)
8	HVAC engineer, BIM expert	Design, engineering, and consultancy	Ramboll Finland is leading engineering, design and consultancy company founded in Denmark
9	HVAC engineer, BIM manager	HVAC design	Granlund in Finland is one of the leading experts in Energy efficiency design, consultancy and software services
10	Structural engineer	Structural engineering	IdeaStructura is based on structural and physical engineering competence and used data modelling in reconstruction
11	Structural engineer	Engineering	Sweco Finland is a set of European engineering consultancy companies focused on construction, architecture, and environmental engineering
12	Project manager	Engineering	A-Insinöörit as a company is specialized in construction and design
13	Design coordinator	Contractor	YIT Finland (in Finnish: Yleinen Insinööritoimisto), is the largest residential construction company in Finland
14	Design Manager	Contractor	Skanska is a multinational construction and development company based in Sweden
15	Design Manager	Property owner	Finavia is a limited corporation fully owned by the Finnish state. Finavia is responsible for maintaining and developing 21 airports in Finland
16	Project manager	Property owner	City of Espoo (in Finnish: Espoon Kaupunki) has its own municipality, which is the second largest city in Finland, sharing borders with Helsinki and Vantaa regions
17	Project manager	Property owner	HUS kiinteistöt provides Facility management and services and is fully owned by the Hospital district of Helsinki and greater Helsinki (Uusimaa) area
18	BIM expert, architect	Property owner	Senate Properties (in Finnish: Senaatti-kiinteistöt), is a Finnish unincorporated, fully state-owned enterprise, under the Finnish Ministry of Finance
19	BIM Coordinator	BIM consultancy	Gravicon is an IT consultant and developer for building industry specialized in BIM consulting services.

3. POTENTIAL OF BIM IN PERFORMANCE BASED DESIGN

3.1 Generic benefits of BIM in design process

The generic benefits of BIM have been discussed and evaluated by several studies. Barlish and Sullivan (2012) compared non-BIM and BIM projects and made preliminary estimates of overall savings and benefits. According to them the most important benefits of BIM concern scheduling, sequencing coordination, rework, visualization, productivity, project cost, communication, design/engineering, physical conflicts, labour, and quality and simulation.

BIM models generated digitally can provide design models together with accurate and fundamental information for decision making through a standard method of storing this information, thereby facilitating sharing of information, visualization and improving collaboration (Eastman *et al.*, 2011; Rancane, 2014). As presented in Table 3, improvement in visualization and coordination is especially emphasized by the NBS National BIM report (RIBA Enterprises Ltd, 2014) and the Finnish BIM survey (Finne *et al.*, 2013). Quite consistent with this, Bryde *et al.* (2013) reported that cost reduction through the project life cycle, time reduction, communication improvement, coordination improvement, quality increase, negative risk reduction and scope clarification (listed in the order of importance) are the most important success criterion of using BIM resulting in positive benefits. Many studies emphasize the benefits of BIM in promoting collaboration of team members from different design disciplines and interaction (Eadie *et al.*, 2013; Elmualim and Gilder, 2013; Porwal and Hewage, 2013; Saini and Mhaske, 2013).

In the UK, the use of BIM has been defined as BIM Maturity levels and categorized as a maturity index in four (0-3) levels. At level three, BIM would support cost estimation, thermal properties analysis, operational applications, and lifecycle management as part of the process. Level three 'intends to use open process and data integration through web services which are compliant with the emerging IFC/IFD (International Framework for Dictionaries) standards' (BIM Industry Working Group, 2011). Malleson (2014), stated that the level of use is moderately good in Britain, but there is still much to do before the overall building performance is managed in different project phases with the help of BIM. Becerik-Gerber and Rice (2010) presented that the lack of proper experience in the use of BIM hinders the determination of the value of BIM.

Table 3: Benefits of BIM based on NBS National BIM report 2014 and Finnish BIM survey 2013.

Claimed benefits	Percentage of respondents that agreed with the claims in the survey conducted in NBS National BIM report (<i>n=1000</i>)	Percentage of respondents that agreed with the claim in the Finnish BIM survey (<i>n= 400</i>)
Visualization	83	85
Coordination of construction documents	77	39
Data management	<i>not assessed individually</i>	77
Cost savings	61	24
Speed of delivery	52	22
Profitability	45	27
Use of COBie* in projects	23	8

* Construction Operations Building information exchange (COBie)

Kreider et al. (2010) have studied the use frequency and benefits of applying BIM on projects with the help of a survey. Among the perceived benefits and use frequency of 3D modelling, design reviews, and design authoring was assessed most positively among other BIM uses. The survey results reveal that, BIM has the potential for energy analysis, sustainability analysis, mechanical analysis and lighting analysis although the use frequency of BIM is moderately low. Even though BIM can support the assessment of many performance-based criteria of the building, the AEC industry doesn't have a streamlined process to achieve desired results as it depends greatly on the interoperability of the software used to conduct the analysis. Also, Bynum et al. (2013) highlighted the interoperability problems that hinder the use of BIM in different kinds of building performance analyses. In summary, the results of the above surveys and corresponding studies reinforce that BIM is very successful in terms of managing the performance of the project.

3.2 BIM support for building performance simulation (BPS) and assessment methods

Building performance simulations are typically done separately and independently of each other in different design phases (Cho et al., 2009). There are still large challenges in implementing BIM-based sustainability analyses because of the lack of process models and practical strategies for integration of information (Lim, 2015). This section intends to focus on BIM-based and BPS-based aspects of the tools. We also assume that, the presented BPS tools (Table 4) are known to the architects and other representatives of design disciplines being wide spread in academia and AEC industry. This section gives an overview of the status of different simulation tools, their ability to exchange information with BIM and the ability of BIM to support BPS (objective 1). The focus is on widely used commercial tools that support the simulation of energy performance (section 3.2.1); environmental performance (section 3.2.2); indoor air quality (section 3.2.3); lighting (section 3.2.4), and acoustics (section 3.2.5). Approaches such as that of 'tools and platforms' for integrated design assessment are discussed in section 3.2.6. Table 4 summarizes the results of the literature review linking the BIM-based model with BPS-based tools/software.

3.2.1 Energy performance assessment

Energy performance assessment and simulation have become increasingly popular research topics in BIM research (Yalcinkaya and Singh, 2015). A high number of BPS tools with a range of capabilities are available. The choice of tools depends on the ability to perform the needed assessment. When aiming to obtain accurate assessment results, sophisticated dynamic energy simulation methods must be used, like those applied in, e.g., Energy Plus (Crawley *et al.*, 2008) or the IDA ICE program (Sahlin, 1996). These tools require the modelling of the whole

building considering the characteristics, such as volume, form, orientation, window sizes, heat-insulation, dynamic environmental conditions, and HVAC components. This information can be brought to the simulation tool from the BIM-based design model by using directly or indirectly IFC compatible tools, for example (Bazjanac, 2008). Until now, the AEC industry has not found an absolute solution to derive a coherent process for efficient use of BIM information for energy optimization purposes (Asmi *et al.*, 2015; Robert *et al.*, 2012) and there are in fact many studies presenting semi-automated approaches such as that of (Barnes and Castro-Lacouture, 2009; Bazjanac, 2008; Cemesova *et al.*, 2015; Cormier *et al.*, 2011; Geyer, 2012). Also, Ahn *et al.* (2014) pointed out that IFC is not ready to include all needed information for the simulation. The details of mechanical systems applied to dynamic simulation tools are still unstructured in the IFC format, and it is difficult to accurately convert IFC to a well-structured simulation information model. Some part of the needed information should be captured in external sources (e.g., weather data), and some could be linked to the BIM-based model by using a standard approach (e.g., product data).

Although many simulation tools can utilize IFC, the generation of an building energy performance (BEP) simulation model from BIM-based model is still time-consuming because it may include unnecessary information and on the other hand may lack the needed information (Kim *et al.*, 2015). Data extraction and data exchange are two key processes associated with the interoperability among BIM applications. Also noted by Lu *et al.* (2017), to support the required performance analyses, BIM data requires many modifications which weakens the design benefits. Significant time savings can be achieved when there is no need to create the building geometry in energy simulation model but there is a high risk for missing, misplaced, or deformed building elements during a BIM data exchange process, also reported by Oh *et al.* (2015) and Senave and Boeykens (2015). An object-based approach in which the geometry and material information needed to build an energy input file able to collect data from a model authoring software parsed for energy simulation may yield higher accuracy (Kim *et al.*, 2015).

‘BIM-based model extension can be achieved by extending data through subclass like IFC property sets’ (BuildingSMART International, 2007) but the extended IFC model is deficient in semantic information. Though, the most recent version of IFC4 also ‘does not allow the specification of all elements required to express HVAC systems’ (Asmi *et al.*, 2015) and BIM-based specification is rather poorly addressed (Robert *et al.*, 2012). Thermal comfort is very often evaluated together with the energy performance assessment of buildings. Some property sets in IFC exist only as a notion of thermal comfort linked with the HVAC design parameters (air temperature, mean radiant temperature, air velocity, and relative humidity) and the thermal environment caused by the choice of building components eg: PsetSpaceThermalPHistory, SpaceThermalRequirements etc. (Huovila *et al.*, 2014). Accounting for the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) is also acknowledged by ISO 7730 (2005). Most of the commercial BEP software, such as IDA ICE, accounts for PMV and PPD. However, as noted by Soubra *et al.* (2012) IFC schema doesn’t contain specific Psets to include thermal comfort specifically as it is considered as a building ‘use phase’ parameter, and should be introduced.

BuildingSMART alliance developed the Information Delivery Manual (IDM) approach to identify the processes and information flow during the life cycle of a facility (buildingSMART International, 2017a). The objective of IDM has been to provide a method to capture and specify the semantically rich information required by the IFC schema. Model view definition (MVD) or IFC View definition is a mechanism proposed by the standardisation organisation buildingSMART for defining the subset of the IFC data model that is necessary to support a specific data exchange, such as energy simulation (buildingSMART International, 2017b). It is intended to overcome the complexity and large size of IFC data models (buildingSMART International, 2017a), but from perspective of BEP, MVDs have been specified only for energy and structural analysis. Liu *et al.* (2013) introduced an IDM approach to identify information requirements for performance analysis of HVAC systems, where they had to make changes to the original IDM approach. The official certification is currently available only for IFC Coordination view (buildingSMART International, 2017c), so exact information of software implementing these MVDs is not easy to achieve. Moreover, as presented in Table 4 none of the BPS analysis and simulation software’s listed in buildingSMART application category with IFC compatibility are MVD supported (buildingSMART, 2017).

Another challenge lies in exporting the results of the best BEP solution back to the design BIM model solutions after the simulations are conducted. Even if the design and simulation tool is directly or indirectly IFC compatible, none can export information back to the BIM model even through an “intermediary” as explained in detail by Bazjanac (2005) and Soubra *et al.* (2012). Thus, the BIM model has to be manually updated after simulations if the design needs to be altered after the energy simulations. This unidirectional approach of information exchange is unable to inform building design in a streamlined manner. Approaches based on automatic bi-directional

exchange of data workflows, enable designers and architects to make parametric changes to the BIM model and simulate the energy performance or other performance aspects simultaneously for example: Asl et al. (2013) and Turrin et al. (2011). Even though at an experimental stage, such approaches have paved the path for enhanced decision-making capability, and it remains curious if we see the influence of this trend applied in AEC practice at large.

3.2.2 Environmental performance

The assessment of embodied environmental impacts (all impacts related to materials and products such as impact because of extraction of raw materials, manufacturing, transportation, installation etc.) happens by combining the information about material types and quantities with the data of the environmental impacts of these materials (Alwan and Jones, 2014; Wang *et al.*, 2011). BIM supports the assessment of embodied impacts by offering the rapid assessment of material quantities (Jalaei and Jrade 2014). Also, Matthews and Capper (2012) and Kulahcioglu et al. (2012) suggest that the consideration of embodied impacts can be done by combining environmental data about materials and products with model-based information about quantities based on the model using IFC as a data sharing format. The external data can be taken from product libraries with the help of IFC-based implementation (Soubra *et al.*, 2012). IFCs also incorporate a mechanism called Property Sets. As explained earlier, this allows the information provider to allocate new properties to an object in a BIM model and consider different kinds of embodied impacts. ILMARI (VTT Technical Research Centre of Finland, 2017) and ELODIE (CSTB, 2017) are examples of publicly available tools for BIM-based environmental assessment. ILMARI combines IFC-based quantity take-off data from design software with generic carbon footprint data of products saved in ILMARI software. ELODIE combines external Environmental Performance Data (EPD) with quantities of building elements defined with the help of a model viewer. This allows the selection of the building parts to be included in the Life cycle assessment.

Jalaei and Jrade (2014) suggest BIM compatible plug-in tool which supports product suppliers' web pages by cataloging green components and their environmental characteristics. Basbagill et al. (2012) recommend considering embodied impacts already in early phases of design; material quantity formulas and embodied GHG emission factors can be embedded in the BIM authoring tool. Also, Diaz and Anton (2014) and Anton and Diaz (2014) compare the benefits of two alternative approaches. First, when the assessment is done with the help of a separate assessment tool by importing the model-based quantity information via IFC, there is no need for manual data transfer. However, the effects of any changes in the design can only be evaluated by going back to the model and re-importing the quantity data back to the assessment software. Second approach is to include LCA information in the BIM objects instead of using external databases that could better support designers' understanding of environmental issues in early design phases (Antón and Díaz, 2014). However, the use of external databases offers more flexibility to use various sources and easier maintainability of environmental data.

Tsikos et al. (2017) propose a method that consists of an integrated dynamic model. In this approach, Revit is used with an external material life Cycle Inventory (LCI) database in connection with the visual programming language Dynamo. There is a permanent link with unique material IDs from Revit to an external database that includes life cycle inventory-based environmental information for materials per a specific functional unit (m^3 or m^2). The material take-off and environmental information are collected in the same script and finally exported in a new excel sheet which generates necessary graphs and charts. Similarly, Abanda et al. (2017) also address the problem of material IDs, where they manually edited 57 concepts in Revit material database to use as input in their proposed system. To apply British New Rules of Measurement 1 (NRM), they used Naviswork as an intermediary to avoid the loss of information about structures while following the NRM methodology. NRM ontology was mapped to XML codes loaded in Navisworks and were then exported to a spreadsheet using Revit as an interface. The environmental information based on Bath Inventory of Carbon and Energy was structured accordingly.

Several solutions have been presented for the linkage of quantity data and environmental data in BIM-based environmental assessment procedures, but none of them are generic. The problem of linking environmental data becomes more complicated when different environmental data sources are required to be used during the assessment process. During concept, developed and technical phases of design (see Table 3) generic data is needed as the specific manufacturers and their specific products have not yet been selected. Nonetheless, during the construction phase, the environmental impact should be calculated based on as-built information, and correspondingly specific data should be used available in environmental product declarations (EPDs).

3.2.3 Indoor air quality assessment

Indoor air quality plays an intrinsic role in occupant comfort, and should be evaluated as a key building performance evaluation criterion. Indoor air quality modelling categories include, statistical models eg., SHAPE (Ott, 1984), material/mass balance models eg, RISK (Sparks, 1996) and CONTAM, and Computational Fluid Dynamics (CFD) models (Sparks, 2003). The Multizone Airflow and Contaminant Transport Analysis Software (CONTAM) is suitable for assessing indoor air quality (IAQ) in multi-zone buildings for e.g., with multiple rooms and floors (National Institute of Standards and Technology (NIST), 2017). A number of studies have integrated multi-zone indoor air quality and fluid dynamics computation with energy simulation software, such as TRNSYS and EnergyPlus, to evaluate the relationship between IAQ and building energy consumption (Deru *et al.*, 2011; Dols *et al.*, 2016; Drogemuller, 2006; Laine *et al.*, 2000; McDowell *et al.*, 2003; Ng *et al.*, 2012, 2015, 2018). Chen *et al.* (2015) describes an integrated simulation environment for energy efficiency and IAQ analysis with the help of EnergyPlus and an enhanced CHAMPS-Multizone model. It enables the simulation of combined heat, air, moisture, pollutant transport and daylighting for a whole building. Salis *et al.* (2017) describes the complexity of assessing IAQ in low-energy buildings and proposed four IAQ indices as part of IEA EBC Annex 68 to provide a quantitative measure. In the same study, they also reported that there is too limited data on the level of indoor air pollutants in low-energy residential buildings. Availability of limited data further deepens the challenge of providing reference values to compare the obtained IAQ simulation results (Ng *et al.*, 2012).

Input data required for the simple modelling of IAQ can be broadly categorized under physical condition (location or building), chemical contaminants (indoor/outdoor), biological contaminants (indoor/outdoor), etc. Depending on the type of analysis required, contaminate transport analysis can be performed for e.g. CO₂, Ozone, particulates less than 2.5 µm and generic volatile organic compounds (Hussein and Kulmala, 2008). IAQ assessment requires information about indoor pollutants as input data and much of this data is dependent on the activities carried out in the building during occupancy is difficult to be captured in BIM-based model. Recent research efforts have focused on proposing extensions to IFC data set for IAQ properties, such as including the concentration of CO₂ during occupancy and formaldehyde concentrations (Huovila *et al.*, 2014). However, IAQ is very complex due to a plethora of chemical compounds in the indoor air, and the information needed to fully comply with perceived air quality measures are too detailed to be captured by an IFC model on one particular dynamic calculation tool. Research efforts are needed in this direction, as IAQ should not be over looked to be applied only during the buildings 'use phase', similar to that of thermal comfort as discussed by Huovila *et al.* (2014). The part of the input data required for the IAQ assessment during the early phases of design such as a type of the building, expected occupancy, and details of the HVAC from the technical design phase can be obtained through external product libraries which could be linked to BIM.

3.2.4 Lighting assessment

Factors such as in-depth illuminance, luminance, and daylight glare probability are calculated by specific software solutions such as DIALux (DIALux, 2017a), Radiance (Berkeley Lab, 2017), ReluxSuite (Relux Informatik AG, 2017) and others (Acosta *et al.*, 2015). In April 2017, DIALux became the first lighting specific software to release IFC import functionalities allowing the import of BIM-based models (DIALux, 2017b). Even though, it support import of only few objects, and export functionalities are underdevelopment and are expected to be released in 2018 (based on e-mail communication). Lighting simulations such as Radiance use three-dimensional geometrical description of a scene and physical properties of materials as input data. It is possible to store the information about the properties of a lighting fixture and its photometric data in the BIM-based model and this data can be transferred to simulation in theory, though external databases of photometric data are used for example by DIALux and Relux (Ochoa *et al.*, 2012). There are also several examples of semi-automated and computation approaches where energy simulation has been integrated with in-depth lighting studies (Mavromatidis, 2015; Mavromatidis *et al.*, 2014; Tagliabue *et al.*, 2012). BIM does not have all the information that is necessary for creating the simulation input files for Radiance but it provides options to incorporate the required information. Kota *et al.* (2014) presented a method to enable direct integration of BIM with daylighting simulation tools. The same study identified that the representations of some elements are not identical between Revit and Radiance; for example, a glass pane represented with a thickness in Revit has to be represented as a surface without a thickness in Radiance. Their prototype creates input files from Revit models to Radiance and DAYSIM simulation tool through automated steps with high accuracy.

There seem to be two kinds of approaches for lighting simulations, the first where the calculation algorithms are embedded in the BIM authoring software and second, where the assessment uses proprietary software-developer-specific file formats for design software. For example, Liu et al. (2015) introduce the use of Ecotect Analysis BIM software produced by Autodesk in lighting performance and thermal performance simulations, however, Ecotect Analysis is now discontinued (ECOTECT, 2015).

3.2.5 Acoustical performance

The acoustic simulation process consists of fundamental steps of collecting necessary data about acoustic qualities of the architecture, simulating sound propagation, modifying a sound sample with the simulation results, and listening to simulated sound (known as auralisation) and inspecting the sound characteristics both numerically and graphically (Wu and Clayton, 2013). Four sets of input data are needed when performing an acoustic simulation of an indoor space: the geometry of the room, finish materials of the room with the absorption characteristics at various frequencies, sound source, and audience (Wu and Clayton, 2013). An approach of developing IFC assembler program that would both read and write to the IFC file refer to the construction database to populate IFC file with corresponding acoustical properties (Vedvik and Mooney, 2011). BIM has the potential to deliver information of room geometry and its material characteristics. For example from Citherlet and Hand (2002, p. 849), “an office room might be modelled as a single thermal zone for the energy performance analysis. In this case, the acoustic zone boundaries correspond to the thermal zone boundaries and the volume used to assess the reverberation time is equal to the volume delimited by the thermal zone”. Mapping essential parameters such as sound intensity level, reverberation, absorption coefficient and transmission losses can be directly extracted from BIM-authoring software. There is evidence from construction industry manufactures who released their acoustic slabs as BIM objects (Paroc Group Oyj, 2014) and produces their own EPD’s with third party certification (Paroc Group Oyj, 2016), but the commonly used acoustic software’s are not interoperable with IFC.

There are many commercial software applications for acoustic simulations such as (CATT-Acoustic, 2011; EASE, 2017; Odeon, 2017; RAMSETE, 2007; SoundPlan, 2017) among others. For prediction and evaluation of noise barrier performance, tools such as that of CadnaA noise prediction software (DataKustik GmbH, 2017a), CadnaR-calculation and Assessment of Interior Sound (DataKustik GmbH, 2017b), Bastian-building acoustics planning system (DataKustik GmbH, 2017), LimaA (Softnoise GmbH, 2017) environmental noise projects, Immi, MicroBruit are used. For the computation of noise at building projects such as that of airport, cityscapes ECAC Doc. 29-Interim, Predictor 8.11 is commonly used (Sari *et al.*, 2014). Some of these applications allow the import of geometry representations produced by CAD programs and permit the user to assign absorption coefficients to each face (Wu and Clayton, 2013). Although these applications require additional work to assign acoustic properties to each face, some of them are proven to be excellent in accuracy (Bradley and Wang, 2007; Vorlander, 2010). However, there is greater risk of input uncertainty, model uncertainty and uncertainty in assignment of noise level (Shilton, 2017).

Possibilities for BIM integrated acoustical analysis are presented by, e.g. Lepage (2010) and Sunvoun *et al.* (2013), but neither represent an IFC-based approach. Deng et al. (2016) achieved BIM and 3D GIS noise mapping by developing a data integration engine to allow bidirectional conversion between major data schemas in BIM and GIS in a virtual design and construction (VDC) process using Italian C.N.R. model. The trend of virtual reality in AEC industry is already catching up with acoustics engineering. For example, Cundall Virtual Acoustic Reality (VAR) links a 3D graphics program, -Unity, with the CATT Acoustic software which allows the stakeholders to immersive audio visual experience in a virtual building environment (Cundall, 2016).

To summarise, two kinds of approaches have been presented in research for utilising BIM: the first retrieves only geometry information from BIM and adds acoustical characteristics of spaces using an acoustical database (Vedvik and Mooney, 2011); in the second approach, BIM is first "enriched" by inputting acoustical characteristic parameters into the model and then all of the data is extracted from BIM to the simulation engine (Wu and Clayton, 2013).

During the literature search, the authors exhausted a broad range of keywords, and in fact could not find publications integrating BIM and Acoustic simulations. This study reconfirms that there is no scientific evidence of the current commercial software to the knowledge of authors that can use "enriched" BIM that includes acoustic data. From the viewpoint of simulation tools, BIM files are complex and include unnecessary information. Typically, BIM data will have complex textural information and metadata. The inclusion of this data for room

acoustic prediction requires much simplification together with a rendering strategy that presents the most subjectively important features of the soundscape while preserving validity as stated by Drumm and O'Hare (2015).

3.2.6 Tools and platforms for integrated design assessment and enriching BIM

There is not yet a single way to comprehensively utilise BIM-based model data for assessing several performance aspects of a building. The research on integrated BIM tools (BIM platforms, BIM servers, collaboration tools, project data management tools) focuses especially on data storage and sharing, communication, and workflow management related features (Jaradat *et al.*, 2013; Singh and Gu, 2012). Also, Chen *et al.* (2015) claim that there is a general lack of studies on BIM interoperability among different BIM software. However, some research has been conducted on tools which would integrate multiple assessments to one platform unifying design and calculation tool (Aouad *et al.*, 2005; Negendahl, 2015), offer an integrated framework for BIM-based performance optimisation (Jalaei and Jrade, 2014), or provide processing of BIM models so that multiple assessments can be run with them (Sanguinetti *et al.*, 2012). According to Charalambous *et al.* (2012), the potential of BIM combined with online collaboration platforms, provides an opportunity for addressing many building industry obstacles such as fragmentation and adversarial relationships.

nD-modelling (where 'n' is the number of dimensions 'D' which can be interpreted as parameters) tool prototype presented by Aouad *et al.* (2005) aims at aiding an integrated design. The target is to integrate some design dimensions into a holistic model, which would encourage and support the project team to systematically assess and compare the strengths and weaknesses of different design scenarios. The greatest benefit of this approach was the capture of knowledge without losing data. However, they reported that interoperability should be considerably developed to enable 'what-if' analyses of buildings.

Pinheiro *et al.* (2015) proposed a BIM-based life-cycle performance evaluation framework to improve building performance analysis. The paper describes an IDM/MVD mechanism that provides a structured framework for the definition and exchange of building data for building performance analysis by gathering all information from heterogeneous sources and by converting it to a common data format. The result is an IFC compliant framework for the assessment of buildings. However, the authors found out that technical documentation for the MVD is still missing.

Investigation by Sanguinetti *et al.* (2012) offered a post-processing approach for BIM models to run multiple analyses based on a single BIM model without the designer having to prepare the model separately for each analysis. The presented examples include space program validation, circulation validation (requirement of user-specific access to specific parts of the building), cost estimation and energy analysis. A tool was generated to extract data from BIM and embed domain-specific requirements for different analysis tools. Similarly, Bakis *et al.* (2007) discussed the need for such intervening tools.

One of the draw-backs in IFC-based interoperability is that whenever the model is updated (and new IFC file is generated) the linkage of the input data from BIM and other analysis specific input data has to be started over. Improved functionality should be developed to retrieve the changes in IFC file to ease the update process regarding simulation parameters (Vedvik and Mooney, 2011). Another general challenge is the possibility to export results of the best-developed solutions back to the design BIM model. Currently, the bi-directional dataflow solutions are at an experimental phase thus not generic enough to be applied.

The BIM model has to be manually updated after BPS requiring design to be altered according to the obtained results. Based on the above findings from the literature review, it is clear that even though we have made progress within the scientific community on utilizing and enriching BIM, we are still struggling with the implementation of exploiting the availability of the BIM-based data for BPS-based assessment in real building projects. The following section focuses on the current challenges faced by the AEC industry. Table 4 presents the summary of the literature review linking BIM-based models to BPS tools.

Table 4: Literature review linking BIM-based models to BPS tools

Tools for assessing performance based design	Name of the tool and origin	Capability	Import/Export via IFC 2X3 compatibility corresponding to the tool	Examples of required input data in BPS tools	Linking BIM-based data with BPS-based simulation*
3.2.1 Energy performance (Heating energy, cooling energy, HVAC systems and thermal comfort)	IDA ICE, EQUA Simulation AB, Sweden	Energy simulation	Import (buildingSMART International, 2017d; EQUA Simulation AB, 2011)	Ahmed et al. (2015); Hilliaho et al. (2015); Jung et al. (2018); Soleimani-Mohseni et al. (2016)	Giannakis et al. (2015); Jung et al. (2018); Nageler et al. (2017)
	RIUSKA, Granlund Oy, Finland	Comfort and energy simulation. Software based on DOE-2	Import and Export (buildingSMART International, 2017a)	Mitchell et al. (2007); Pietaril, (2013)	Gupta et al. (2014); Laine and Karola (2007); Lilis et al. (2017); Maile et al. (2007)
	Simergy, LBNL, USA	Building Energy Modeling (BEM) front end to DOE EnergyPlus simulation engine	Import (buildingSMART International, 2017b); Export (Lawrence Berkeley National Laboratory, 2017)	Cao et al. (2014); Lawrence Berkeley National Laboratory (2017)	Chen et al. (2017); Remmen et al. (2015)
	OpenStudio, NREL/U.S. DOE, USA	BEM using EnergyPlus and advance daylighting using radiance	Import (buildingSMART International, 2017c)	Bazjanac et al. (2011); Cho et al. (2009); Tagliabue et al. (2012)	Lee et al. (2015); Parker et al. (2017)
	IESVE, offices worldwide	Integrated Environmental Solutions (IES) Virtual Environment (VE), Multiple integrated application	Import (buildingSMART International, 2017d); interoperable with Revit, Sketch up, DXF, gbXML and Vectorworks (Integrated Environmental Solutions Ltd., 2017)	Cho et al. (2009); Micono and Zanzottera (2015); Mostafavi et al. (2015)	Habibi (2017)
	Energy Plus U.S. DOE, USA	Energy simulation console-based program	Indirectly interoperable with IFC. (1) can translate IFC file to Energy plus using GST and BimServer (a native IFC database) OpenStudio plug-in for example Senave and Boeykens (2015); (2) can be linked to co-simulation programme by using- one to one coupling, middleware coupling and via Functional Mock Ups (FMUs) as presented by Nouidui <i>et al.</i> (2014); U.S. Department of Energy (2017)	Cho et al. (2009); Gunay et al. (2016); Garcia and Zhu, (2015); Mateus et al. (2014); Pereira et al. (2014); Yang et al. (2015)	Asl et al. (2013, 2014); Choi et al. (2016); Asl et al. (2015)
	TRNSYS, University of Wisconsin, USA	Transient system simulation tool	Not interoperable with IFC. Modular and expansible simulation environment.	Mateus et al. (2014) and many other studies	Boukara and Naamane (2015); Cormier et al. (2011); CSTB Logiciels (2017); Giannakis et al. (2015)

Tools for assessing performance based design	Name of the tool and origin	Capability	Import/Export via IFC 2X3 compatibility corresponding to the tool	Examples of required input data in BPS tools	Linking BIM-based data with BPS-based simulation*
3.2.2 Environmental performance (Life Cycle Analysis)	ILMARI, VTT Finland	Life cycle analysis	Import, the tool can import .xls based quantity take off data generated from BIM authoring software to be used as import to ILMARI	Häkkinen et al. (2015); Ruuska and Häkkinen (2015)	Jalaei and Jade (2014); S. Lee et al. (2015); Shadram et al. (2016)
	ELODIE, CSTB, France	Life cycle ELODIE uses Environmental Product Declarations (EPD) provided by manufacturers and made available through the INIES (www.inies.fr) database (Gantner <i>et al.</i> , 2012)	Import, the tool recommends to first apply FDES-French equivalent to EPDs on the BIM authoring software to embed data on IFC, which can be exported as an .xls to be used as an import to ELODIE	Chevalier et al. (2010); CSTB (2017)	-
3.2.3 Indoor air quality	CONTAM, NIST, USA	Contaminant transport analysis	Not interoperable with IFC.	Salis et al. (2017); Ng et al. (2015, 2018)	Altaf (2011); Y. Chen et al. (2015); Li (2013)
	COMIS	Multi-zone Air Flow Modelling (COMIS)	Not interoperable with IFC. However, Energy plus V2.0 onwards include links to multi-zone air flow engine COMIS and SPARK (Maile <i>et al.</i> , 2007)	Hussein and Kulmala (2008); Warren (2000)	
3.2.4 Lighting	DIALux, DIAL GmbH, Germany	Simulation software to design, calculate and visualize lighting	IFC import available in version DIALux evo 7.0 released April 2017(DIALux, 2017b); IFC export capabilities expected in 2018 (based on email correspondence with DIALux)	Acosta et al. (2015); Jayashri and Arvind (2013); Kovacic and Zoller (2015)	Mavromatidis (2015); Mavromatidis et al. (2014); Tagliabue et al. (2012)
	ReluxSuite, Relux Informatik AG, Switzerland	Simulation software for artificial light and daylight	Not interoperable with IFC. For input, gbXML can be used to import 3D geometry, ReluxCAD available as an add-on to Autodesk Revit for specific lighting tasks, exports results in DWG/DXF (based on email correspondence with Relux)	Acosta et al. (2015); Ochoa et al. (2012); Shailesh and Raikar (2010); Yu et al. (2014)	-
	Radiance, Berkeley Lab, USA	Suite of programs for the analysis and visualization of lighting in design	Not interoperable with IFC.	Naboni (2013); Torres and Sakamoto (2007); Ward (1994)	Kota et al. (2014); Manzan and Pinto (2009); Santos et al. (2017); Welle et al. (2012); Yi and Kim (2015)
	DAYSIM	Simulation engine with plug in capabilities, based on RADIANCE	Not interoperable with IFC. Can import raw input files in 3D model (.obj, .dxf), plug in capabilities: Sketchup & Rhinoceros	Acosta et al. (2015); Flodberg (2012); Flodberg et al. (2012); Reinhart and Wienold (2011)	Caldas and Santos (2016); Gadelhak and Lang (2016); Kota et al. (2014)

Tools for assessing performance based design	Name of the tool and origin	Capability	Import/Export via IFC 2X3 compatibility corresponding to the tool	Examples of required input data in BPS tools	Linking BIM-based data with BPS-based simulation*
3.2.5 Acoustical performance (Geometry of the room, sound propagation, auralisation).	ODEON A/S	Simulating and measuring the interior acoustics of buildings	Not interoperable with IFC. Import of DXF (Drawing Exchange Format) and 3DS format files from CAD software such as: AutoCAD®, Microstation®, 3DS max, IntelliCAD®, Google-Sketchup and Rhino	Gul and Caliskan (2013); Naylor (1993); Passero and Zannin (2010); Rindel (2000, 2002); Zhu et al. (2015)	(1) IFC as schema for BIM, & City Geography Markup Language (CityGML) used to present 3D GIS schema (Deng et al., 2016) (2) Robust Acoustical Templates (RAT) integrated with IFC assembler program (Vedvik and Mooney, 2011) (3) A software porotype using Autodesk Revit, the Revit API, the DirectX toolkit, and C# programming in Visual Studio (Wu and Clayton, 2013)
	CATT-Acoustic	For room acoustics prediction and auralization	Not interoperable with IFC. Support AutoCAD or other CAD plugins, can export VRML 2.0 export. File conversion utilities available for MATLAB .MAT, MLSSA .TIM, .WAV, Lake .SIM,	Alvarez-Morales and Martellotta (2015); Sequeira and Cortínez (2016); Sunyoung et al. (2013)	
	CadnaA, CadnaR, Bastian, Datakustik GmbH	Environmental noise, psychoacoustic parameters for workplace noise and airborne and impact sound transmission between rooms in buildings	Not interoperable with IFC. CadnaA, linked to GIS, support many BMP bitmap-file formats (PSD, DWF, IFF etc.); Bastian can import sketch files (BMP/JPG), noise emission spectra from CadnaA.	Hao and Kang (2014); Margaritis and Kang (2016); Silva et al. (2014)	
	SoundPLAN GmbH	Modular design: Geo-database, road, railway, industrial noise indoor, noise maps, aircraft noise, etc.	Not interoperable with IFC. Interface available for DXF, ASCII sources, LIMA BNA file, ESRIU Shape file, QSI, DBF, ASCII elevation grid, TNM etc.	Bunn and Zannin (2016); Magrini and Lisot (2015); Ozkurt et al. (2014, 2015)	

4. RESULTS OF THE INTERVIEWS

This section presents results of the interviews by explaining different viewpoints to highlight the common practices for conducting simulations and the pertaining problems as experienced by the interviewees (objective 2), if the current simulation methods support performance-based design (objectives 1), and what is needed to improve the current practice (objective 3). This section is split into the qualitative (section 4.1) and the quantitative (section 4.2) results of the expert interviews.

Architects and designers go through several phases of design during the design process of a building; ‘Plan of Work’ provides the description and guidelines for the design process. Accordingly, Finnish plan of work ARK12 (2013), RIBA plan of work (2013), and the American Institute of Architects (2012) used by architects was set as a podium to align the results of the interviews with the design process. This was prepared to gain understanding of the respondents opinion, in terms of which phase of design use of BIM performance-based assessment is implemented. Table 5 presents the importance of BIM utilization is different phases of design. Correspondingly, Section 4.1 is structured as (i) Briefing, Preparation, Concept design, Developed design phases; (ii) Technical design and Construction phases; (iii) Building In-use and warranty period phase.

Table 5: Phases of design in accordance with RIBA/ARK/AIA plan of work and the number of interviewees who pointed out the importance of BIM in different phases of design.

Plan of Work	Corresponding design phases of Finnish, British and American Architects Plan of Work							
Arkkitehtisuunnittelun tehtäväluekello (ARK) Plan of Work 2012 (ARK12, 2013)	0 Briefing	1 Preparation	2 Concept design	3 Generic design	4 Building permission task 5 Technical design	6 Preparation for construction 7 Construction	8 In use 9 Warranty period during use	
Royal Institute of British Architects (RIBA) Plan of work 2013 (Royal Institute of British Architects, 2013)	0 Strategic definition	1 Preparation	2 Concept design	3 Developed design	4 Technical design	5 Construction	6 Handover and close out	7 In-use
The American Institute of Architects (AIA) (The American Institute Of Architects, 2012)	0 Project brief	1 Pre-design/ concept	2 Schematic	3 Design development	4 Construction documents	5 Bidding 6 Construction	7 Commissioning 8 Occupancy	
Importance of BIM in different phases of design	6		13	14	14	8	1	1

4.1 Qualitative results of the interviews

(i) Briefing, Preparation, Concept design, and Developed design phases: Architectural modelling typically starts in the concept design phase but the aim is to utilize BIM already in early design phase starting from the briefing phase. The main phases of BIM utilization are developed design phase and technical design phase (Table 5). Usually, the first purpose of the BIM-based model is to study the massing (sometimes also energy performance), landscape and urban setting of a building. The interviewees noted that, in Finland, architects seldom use energy performance assessment tools (like EcoDesigner included in the architectural modelling software ArchiCAD). Their reasons include the assumed complexity, unwillingness to model the required details and uncertainty of the validity of results. Some interviewees expressed that the use of calculation tools is very time consuming and simulations should mainly be conducted by the engineers specialized in that particular assessment. Interviewees reinforced that the iterative approach is important in designing for high-performance buildings and thus simulation tools are especially needed in collaboration with the engineers. On the other hand, some interviewees addressed that tools are useful only if they do not give too self-evident results (like "decrease windows to improve energy-efficiency"). Only a few interviewees said that alternative models are created in projects to find the best options

for low energy design and sustainable buildings. They emphasised lack of data and the need to develop better access to different kinds of external data (such as product data, geographical data, etc.) needed in the performance assessment. At present, especially the lack of product data or the lack of access to product data hinders the management of certain performance criteria such as service life and maintainability. The interviewees said that much better compatibility of building models and geographical information systems (GIS) models should be developed. Data transfer between computer aided design (CAD) model and GIS model is difficult. However, GIS-data is very useful for many design issues such as consideration of windiness and solar radiation.

Modelling authoring process: The interviewees addressed that the cooperation between different designers, architects and engineers typically starts too late. Every time a new discipline is introduced to the design, changes typically take place. A lot of rework is caused, and at worst case, the design schedule does not allow one to make all changes that would be needed to make the design optimal. Compromises are made between project schedule and performance assessment and design. The interviewees also pointed out that the accuracy and the Level of Detail (LOD) of the model is an essential issue to determine its usefulness. If the level of detail is too high, this demands too much work and makes the use of the model complicated and thus the overall usefulness decreases. If the level of detail of the model is not high enough, the possibility to use it as the basis for assessments is impaired. Thus, the information creation process and its flow are not yet matured and need development. The interviewees also said that tools to assess design in different levels of development are needed. According to interviewees, BIM is still weak in supporting cost-efficient design and construction. There is a need for BIM compatible tools that actually support monitoring and iteration of cost in different phases.

(ii) **Technical design and Construction phases:** Structural engineers use BIM-based models mainly in the developed and technical design stage but sometimes already in early stages of design. HVAC engineers use BIM in developed design stage mainly for defining space requirements. Actual HVAC modelling is done in the technical design phase and onwards. Tools like IDA ICE and the Finnish RIUSKA can retrieve IFC-based data from the model (Gupta *et al.*, 2014; Harish and Kumar, 2016). Typically, HVAC engineers conduct energy performance assessment in concept and developed design phases and use architects' 3D model. Nevertheless, for this purpose, HVAC designers create a separate specific energy model due to inappropriate or incomplete data required in terms of conducting energy performance assessment. During the design process, a lot of calculations and simulations are conducted by the experts with separate tools and often without any linkage to BIM-based models as input data. Many interviewees spoke about the data contents and the related lack of data. One HVAC designer pointed out that the design models include types of information which is not required during the operation phase. In the opinion of the interviewees, both data content and processes (including the maintenance and updating responsibilities of information) should be developed to better utilise BIM during facility management.

Contractors use BIM in the construction phase for production scheduling. Visualization benefits a lot in planning timetables and scheduling work. Large-scale building contractors in Finland develop their skills in using BIM to effectively lead the construction projects. Whereas the interviewees noted that very seldom contractors are seen utilizing BIM during the design phase for steering design and assessing options, although this is largely dependent on the type of the delivery model and the role of the contractor in a specific building project.

(iii) **Building In-use and Warranty period phases:** property owners addressed that models are used for better communication through the design process between the client, users, and designers. Seldom owners or their consultants are seen to use BIM in steering the design and assessing options in the design phase. The interviewees did not refer to any systematic way to use pre-existing BIM models during the use phase of the building. The most urgent task on the basis of the interviews is to enable utilisation of modelled data during building operation. The maintenance guidance should be linked to the model. In addition, the BIM objects could carry useful information about products and their care and maintenance needs, and the information could be searched and visualised in the model (for example "show all rooms with the same flooring type"). It was noted that, often the building does not perform as designed, needs system overhauls and later during the use stage care and maintenance of systems is needed. This would become an easier task if pre-existing BIM data were available to support the multiple renovation cycles during a lifetime of a building.

4.2 Quantitative results of the interviews

It was found that the main motivation of utilizing BIM by the interviewees is either the client requirement or actors own experience of BIM bringing abundance of benefits by streamlining the design and construction process. Most

of the interviewees emphasized both of these criteria. Benefits of utilizing BIM in projects addressed by interviewees are presented in Figure 2. For data analysis and to understand the opinions of interviewees better, they were divided into two groups. Group 1 includes architects, designers, structural and HVAC engineers who are more focused on the design activities. Group 2 represents the project and design managers and BIM coordinators who are focused on the time and scope management of the project and coordination of design and modelling work.

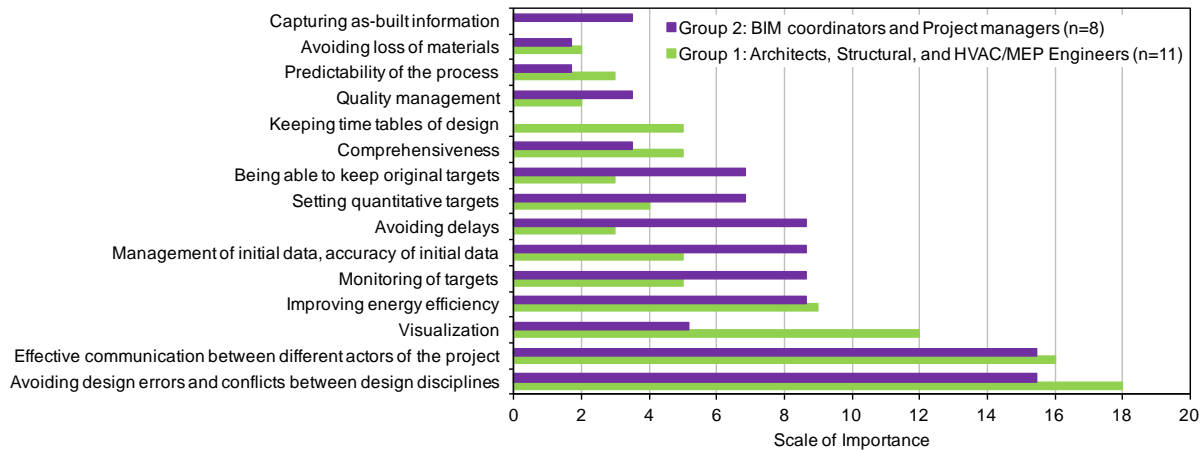


Figure 2: Benefits of utilizing BIM in projects. The responses of group 1 (11 interviewees) were proportioned by multiplying with a size ratio of the group to eliminate the effect of the difference in the number of respondents in group 2 (8 interviewees).

As shown in Figure 3 all interviewees were asked to give zero, 1 or 2 points where zero point denotes the least important and 2 points as the most important benefit observed by them based on their experience (x-axis). The choices presented in y-axis were based upon already established benefits of BIM obtained through literature study before preparing the questionnaire.

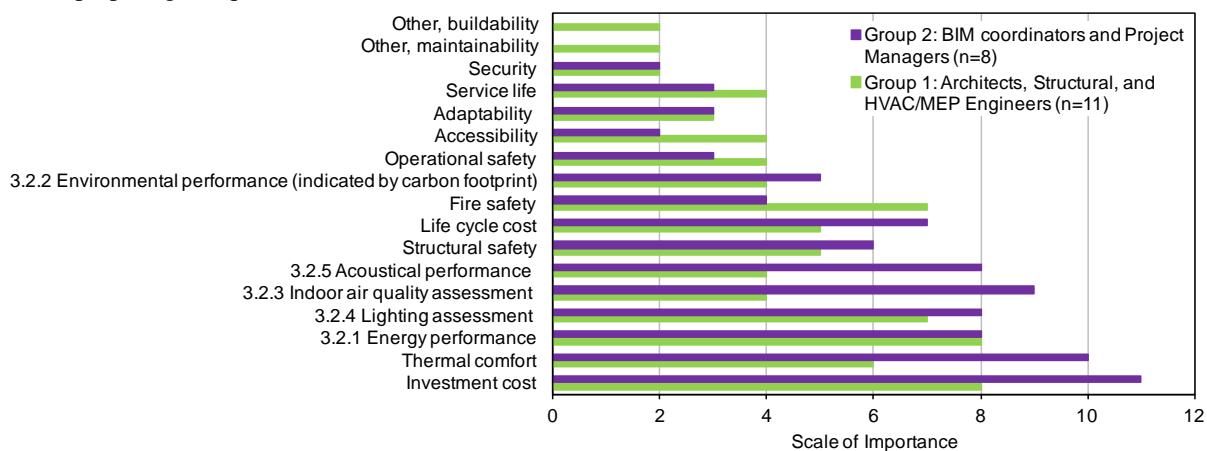


Figure 3: Performance aspects that should be assessed with BIM compatible tools during the design process. All interviewees were asked to denote zero, 1 or 2 points for each aspect based on the importance of the performance aspect in ascending order

BIM supports all actors both within one discipline (like architects to design for better accessibility and flexibility) and across design disciplines, enhancing the communication between the client and designers. Designers and other interviewees were found to have slightly different answers. Managers believe that BIM adds control (e.g., keep targets, monitor targets, avoid delays) while modellers (architects and engineers) value the visualisation. Communication and avoidance of design errors were seen important by all interviewees. HVAC designers addressed that an important motivation is the possibility to utilize the model data for different kinds of simulations. At present, BIM-based data is used for the assessment of energy performance, bill of quantities and costs, and sometimes for the assessment of carbon footprint and barrier-free design. These building performance and Life cycle aspects are evaluated with the help of tools that use BIM-based data.

As presented in Section 4.1 (qualitative) and Table 6 interviewees were asked to freely describe the current use of BIM and address needs for development to improve the performance-based design. The issues seen most important by the interviewees focused on (1) need to develop iterative approaches in sustainable building design, (2) need of support for multi-criteria performance analyses and comprehensive consideration of different performance aspects in collaboration with different designers and other stakeholders, and (3) integration of information, which is needed during operation and in use phases, where pre-existing BIM data can be used after the project is completed. Almost all of the aspects presented in Table 6 were seen as possible through a holistic BIM-based design approach to facilitate and support comprehensive performance assessment of a building by all stakeholders. Table 6 presents the aspects addressed by the interviews in the left column, and the right column presents the number of interviewees who address the same aspect as others. This information was post-processed by the authors to simplify readability and understanding.

Table 6: Current way of using BIM and development needs related to BIM and performance based design addressed by the interviewees

Current way of using BIM		No. of interviewees who addressed this issue
BIM and design phases	The main phases of the use of BIM are developed design phase and technical design phase	14
BIM and simulation tools and comparison of alternative models	Architects seldom use energy performance assessment tools	5
	The use of calculation tools is very time consuming and simulations should mainly be done by engineering specialists	2
	A lot of simulations are done by experts with separate tools and often without linkage to BIM as input data	2
	Alternative models are created seldom to find the best options for low energy design and sustainable building	3
Cooperation and communication during modelling	Cooperation between different designers typically starts too late	3
	Models are used for better communication (between the client, users, and designers) in the developed design stage	3
Development needs		No. of interviewees who addressed this need
Better version control, saving of models for later use and rational design flow		6
Solutions to avoid incompatibility issues among different software		6
Solutions for iterative approach in sustainable building design in collaboration with engineers		9
Better compatibility of BIM models with geographic information systems models and the neighbourhood information models		3
More BIM-compatible simulation tools (for example for energy and cost assessment) that can be used in early phases of design		3
Possibility to provide the pre-existing BIM data for the use of maintenance processes after the construction project is completed		6
BIM compatible tools for service life design		6
Support for multi-criteria performance analyses and comprehensive consideration of different performance aspects in collaboration with different designers and other stakeholders		7
Easy-to-use BIM compatible tools for the assessment of carbon footprint and other simulations		4
Better support for life-cycle cost assessment and design		5
Better linkage to external product data to support environmental design, service life design, or any other performance aspects which require product specific data as input parameters		4
Easy-to-use BIM compatible tools for lighting simulation		3
Visualization of the simulation results with the help of the model		3

5. DISCUSSION

5.1 Future need for performance-based design simulations using BIM-based models

The current potential of BIM for *energy performance assessment* is very high, based on our literature analysis and results obtained through the expert interviews. The main motivation and driver has been the ever-increasing regulations BPIE (2015); European Commission (2012); European Parliament (2010). From the 'availability of tools' point of view, multiple methods and tools exist as presented in the literature review (section 3.1) and capabilities are improving tremendously for example coverage of information retrieved from the model with the help of IFC is high about the requirements of energy simulations. However, high accuracy is needed from the modeller. At present, energy simulations are often done without a linkage for a BIM model. Establishing bi-directional sharing between the IFC data model and the simulation model is one of the limitations that will form the basis for future developments in renewable energy simulation methods (Gupta *et al.*, 2014).

At present, clients' requirements for energy performance are often moderate and can be reached with standard solutions and thus iteration is seldom done. However, the willingness of clients and designers for iterative design process varies, and this may be a strengthening trend especially when requirements for net-zero energy building and plus-energy building has become stronger. The interviewees acknowledged the need for BIM compatible tools for multi-criteria assessment and iterative design processes. Multi-criteria assessment, simultaneous visualization of multiple aspects and optimization are all valid goals. The first actual need for multi-criteria assessment might be the design of zero-energy buildings (ZEBs) in the future. In the design for ZEBs, the energy efficiency must be assessed simultaneously with designing and assessing other performance aspects. The managers (Group 2) valued the indoor environment (IAQ, Acoustics and Thermal comfort) much higher than the designers (Group 1). This could be because BIM managers are in continuous communication with the building owners during the project commissioning, who value the quality of the indoor environment as occupants.

The current potential of BIM for *environmental performance assessment* is high regarding the ease and clarity of approaches based on our literature analysis. BIM supports environmental analyses because the needed information about quantities can be exported from the BIM authoring software with the help of IFC and can be further linked with environmental data of building elements or building materials. The coverage of information retrieved from the model with the help of IFC is good regarding quantities, but it may require further manual handling. The main challenge is to find a good solution for dealing with material IDs. The environmental impact should be calculated based on as-built information, and correspondingly specific data available in environmental product declarations (EPDs) should be used. Different kinds of solutions are available but none of those are generic. However, the potential in practice is still moderately low from the viewpoint of willingness to perform environmental analyses in ordinary design projects. Environmental analyses are typically done in significant construction projects, which aim at sustainability certification. Especially, North American researchers have paid much attention to the potential of BIM to support sustainability (green) certification analyses. However, many European countries are now increasingly emphasizing the meaning of embodied impacts - besides operational environmental impacts - and this is also becoming an issue of building regulations (Bionova, 2017). A probable increase in the willingness to use simulation tools that assess embodied carbon footprint and other environmental impacts by combining BIM-based quantity information with EPDs is expected.

The current potential of BIM for *IAQ assessment* is rated as very low based on our literature analysis and results obtained through the expert interviews. Standards depend on the performance of the HVAC system to provide adequate ventilation to maintain an acceptable ventilation rate per person (L/s-person, see ASHRAE Standards 62.1, 62.2). Some HVAC systems modulate ventilation rates based on indoor CO₂ (human bio-effluent) concentrations, however, such systems do not account for the vast spectrum of particulate and gaseous air pollutants of indoor and outdoor origin that occupants are exposed too. A large proportion of pollutants that affect IAQ during the operational phase originates from indoor sources which are not modelled in BIM. Similarly, HVAC filtration and portable air purification equipment have not been modelled to be stored in BIM-based model. Working on the software specific to contaminant transport (CONTAM) and mass balance analysis (CFD) requires an IAQ expert to be part of the design team, which has not been found to be the case in any published studies to the knowledge of the authors.

Based on the expert interviews, BIM coordinators and project managers (Group 2) rated IAQ as one of the most important aspects to be assessed by using BIM. This reinforces that we need to provide designers with easy to use

tools to assess IAQ at early design stages beyond fulfilling the standard requirements. There are very few studies which have integrated occupational IAQ exposure with BIM and GIS, for example: Altaf (2011) and Li (2013). The IAQ of space is affected by the usage and function of the space. This is why it is important to consider IAQ not only during the design stage but also during the building operation phase. In our hypothesis, IAQ is going to become one of the forthcoming challenges of high-performance buildings. Among many reasons, a few are, that we are moving towards tighter building envelopes by reducing infiltration and using minimum ventilation rates to reduce the electricity usage of the HVAC system. The BIM model itself has a 3D representation of all the spaces, and it can be effectively used to monitor IAQ if systems such as Wang et al., (2010) and Chen et al. (2014) and low-cost IAQ sensing networks are incorporated, eg. Saad et al.(2015).

The current potential of BIM for *lighting assessment* and *acoustical performance* is low, based on our literature analysis and results obtained through the expert interviews. Only one tool (DIALux) used for lighting simulations is BIM compatible. Moreover, none of the acoustical simulation tool are BIM compatible although they require same geometrical and materials characteristics data as input requirement. In principle, BIM has the potential to deliver information of room geometry and material characteristics for lighting simulations. The same applies to the acoustical simulations. Both of these simulations are performed by specialized engineers with the help of specific tools. Question remains, how to ascertain that all of these building performance criteria's are met without having to deal with hackles of interoperability.

5.2 Interoperability and information processes

The literature enlightens many technical perspectives of BIM-based analyses, but interviews reveal more problems that are practical. Some of the current BIM guidance documents provided by large construction clients pay attention to building performance analysis tools in the context of BIM execution plans. In those cases, the considered aspect is typically energy performance (Sacks et al. 2016). A BIM execution plan (The Computer Integrated Construction Research Group, 2010) is a document that should specify the required information and the process to deliver it in a project. To ensure that the models are suitable for use in different simulations, the BIM execution plan must address that (Sacks *et al.*, 2016). Model Level of Development (LOD) has been proposed as a method of specifying the model content and their level of detail in different milestones of the project (Messner *et al.*, 2013). Based on our interviews, application of LOD in practice does not seem to be very clear. 'Level of Detail' is essentially how much detail is included in the model element (Reinhardt and Bedrick, 2017). 'Level of Development' is the degree to which the element's geometry and attached information have been thought through – the degree to which project team members may rely on the information when using the model. In essence, Level of Detail can be thought of as an input to the element, while Level of Development is reliable output. The Finnish common BIM requirements (COBIM, 2012) does not refer to simulations in the context of LOD, and the focus remains on the completeness of the BIM model. There is still debate about the ability of LOD to specify BIM requirements (Bolpagni, 2016; Tredal *et al.*, 2016). The further development of processes and requirements for the LOD of the model in different design phases is needed to satisfy both needs. The better the quality of the input data, the more useful BIM-based model is for performance analyses. A good BIM execution plan should specify the level of development that is to be achieved for each building system and its elements at each milestone of the project (Sacks et al. 2016). With this, much attention should be paid to simulation tools and the quality of the needed input data. The idea of LOD should be further developed and defined corresponding to the stages of design to support iterative design process and the use of simulation tools throughout.

Although the BIM model defines structures and material content of structures and additional information can be included or linked, the nature of data is often text, which cannot be utilized – as not being decipherable – in design, procurement or during operation and maintenance. Classification and structuring of data might improve the possibilities to search and reuse this data. The need for data transfer from the simulation software back to the BIM-based model was addressed by many, which indicates the importance of this problem. Bi-directional approaches do solve this problem, but they are not generic and are user dependent. According to our literature review, there are no tools specifically certified for MVDs performance assessment. Even if in theory a mechanism exists, there is a gap between theory and practice.

The requirements for BIM have increased, especially in public building projects. In model authoring software, more possibilities exist for the presentation or capturing parameters of performance. Very detailed and accurate modelling required by sophisticated simulation software is time-consuming and may not serve for the best efficiency of the overall process. Many tools can retrieve IFC-based BIM data, but still many tools are used

separately and often also independently from BIM data. The literature (Oh *et al.*, 2015) also points out that data losses may occur because the IFC format based information exchange is unable to provide complete interoperability due to structural differences of data conversion mechanisms. The lack of semantic information in the model extended by use of ifcPropertySets can be compensated by an already enriched model to supplement data extension (Asmi *et al.*, 2015).

Aspects that are relatively often assessed with the help of BIM data include costs (based on the bill of quantity); energy performance; some parameters of indoor environment (temperatures, air flows); accessibility (visual assessment, not on the basis of calculations); and embodied carbon (based on the bill of quantity). Based on the interviews, energy and thermal comfort are typically assessed separately from the architect's model. A separate model may be created for example to ensure that all needed information is correctly modelled to form an adequate basis for simulations. However, the implementation agreements (such as IDM/MVDs) for IFC do not necessarily allow exchanging all that information. At present, assessment and simulation tools are typically being integrated into the model authoring software either one by one or used separately. Energy performance (and thermal comfort) have gained most of the attention in the tools evaluating the quality of the building design. It remains curious if the implementation of MVDs will become common and solve the data exchange challenges.

Construction Operations Building Information Exchange (COBie) is applied to support the use and maintenance of the building using the MVD approach to represent the mapping between the required information from various domains (buildingSMART International, 2009, 2011). The interviewed design and simulation experts do not seem to be aware or enabled to use the MVDs in practice. Application of COBie as assessed by NBS National report in the UK is only 23% and based on Finnish BIM survey it is only 8% (Finne *et al.*, 2013; National Building Specification, 2014). The interviewees addressed an urgent need of a systematic way to use pre-existing BIM models during the building operation phase. It remains yet to be seen if the application of COBie can support multi-renovation cycles, which will require as-built information to be rather accurate for facility management processes.

6. CONCLUSION

The main objectives of the study were to study the capability of BIM compatible simulation tools to support performance-based design, explain stakeholders' current ability and barriers in using BIM for performance-based design, and to identify needs of development. The results of the literature review and expert interviews reinforce that BIM is very successful in managing the performance of the project. Concurrently, this also reflects that the current practice of BIM utilization is more focused on 'performance of a project' than the 'performance of the building', and these two facets should be considered simultaneously.

New research needs and knowledge gaps were identified for integrating BIM-based models to performance-based design for Indoor Air Quality, Acoustics and Lighting to provide all key stakeholders ways to assess a building holistically with BIM across all design stages. Based on our study, the current potential of BIM for energy performance assessment was rated as high, for environmental performance assessment it was rated high from the technical point of view, but rated moderately low regarding practical application; for lighting moderately low, for acoustics low, and for IAQ very low. The most important development needs addressed by the interviewees focused on iterative design processes and rational design flow, multi-criteria performance analyses, service life design and usability of BIM in use and maintenance stages, fewer incompatibility issues among different software and better linkage with external data.

Regarding development towards performance-based design, the main challenge remains in the data exchange between BIM authoring tools and performance assessment tools. To improve data exchange - or more specifically the data set needed for different use cases of BIM-based models- more Model View Definitions should be defined and implemented to provide end users with the tools and processes they need. Observations during the study highlight the need for not only technical standardisation but also process standardisation to better understand who should provide each piece of information. To better support performance-based design along the design process and in early phases, further specifications for 'Level of Detail' and 'Level of Development' should be developed. The specifications should consider the viewpoints of performance simulations. Correspondingly, this aspect should also be taken into account in BIM execution plans. Using BIM-based models for performance-based simulations will allow us to achieve high-performance buildings together with comfortable indoor spaces for all stakeholders.

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APPENDIX 1

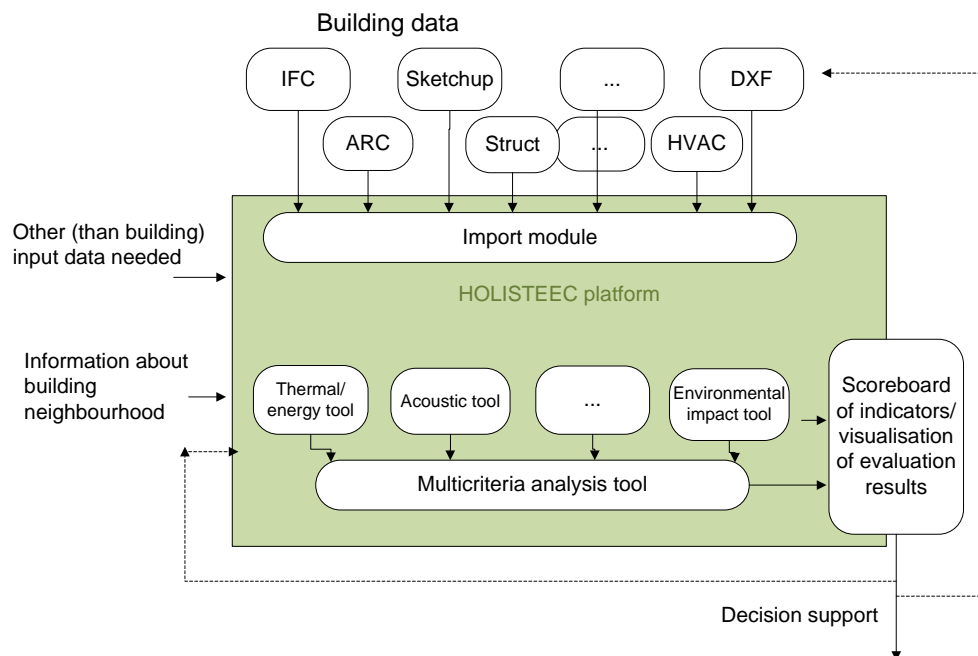
INTERVIEW QUESTIONS

1. Interviewee's name and contact information
2. Short explanation of the role of the company in projects. What is your relation to design or design management?
3. For what purpose do you need BIM in different phases of design?

The phases are predefined as follows.

- Preparation and brief
 - Concept design
 - Developed design
 - Technical design
 - Construction
 - Handover
 - In-use
4. What is your main motivation and driver for exploiting BIM?
 5. What are the most important specific benefits of BIM?
 - ++ very important
 - + important
 - - not important
 - setting quantitative targets
 - monitoring of targets
 - more efficient communication between different actors of the project
 - avoiding design errors and conflicts between design disciplines
 - management of initial data, correctness of initial data
 - comprehensiveness (simultaneous management of infra + building data)
 - predictability of the process
 - avoiding delays
 - improving energy efficiency
 - keeping time tables of design
 - being able to keep original targets
 - avoiding loss of materials
 - other (define)
 6. Which are the most important performance aspects the evaluation of which need BIM compatible tools
 - ++ very important
 - + important
 - - not important
 - indoor air quality
 - thermal comfort
 - acoustics
 - lighting
 - fire safety
 - structural safety
 - operational safety
 - security
 - accessibility
 - flexibility
 - service life
 - investment cost
 - life cycle cost
 - energy performance
 - carbon footprint
 7. What aspects should be quantitatively monitored (by setting a quantitative target which can be compared to calculated/assessed result)?
 - indoor air quality
 - thermal comfort
 - acoustics
 - lighting
 - fire safety
 - structural safety
 - operational safety
 - security

- accessibility
 - flexibility
 - service life
 - investment cost
 - life cycle cost
 - energy performance
 - carbon footprint
8. How are these aspects assessed? Are there proper methods and tools to deal with those aspects in different phases of design, construction and operation to ensure the targeted performance? If not, what kind of tools would be needed?
- indoor air quality
 - thermal comfort
 - acoustics
 - lighting
 - fire safety
 - structural safety
 - operational safety
 - security
 - accessibility
 - flexibility
 - service life
 - investment cost
 - life cycle cost
 - energy performance
 - carbon footprint
9. What are the differences between new building and renovation projects in
- a) using BIM?
 - b) performance assessment and assessed aspects?
10. Is there a need for simultaneous and common consideration of different aspects at the same time? Are there tools for that?
11. We are currently developing a holistic platform to support performance based design by providing a “dashboard” for the management, a requirement setting tool, simulation tools that retrieve data from the model, and a “scoreboard” to enable the comparison of results (Figure 1). How a platform like this should support performance based design? Should the platform support multi-criteria optimization?



Planned structure of the HOLISTEEC platform

12. What other features/qualities the platform should have in order to help in the current BIM process (design, modelling, communication, simulation, design management, project management)?