



BUILDING INFORMATION MODELING (BIM) FOR INDOOR ENVIRONMENTAL PERFORMANCE ANALYSIS

Civil and Architectural Engineering
Technical Report CAE-TR-3



DATA SHEET

Title: BUILDING INFORMATION MODELING (BIM) for Indoor Environmental Performance Analysis

Subtitle: Civil and Architectural Engineering

Series title and no.: Technical report CAE-TR-3

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Internet version: The report is available in electronic format (pdf) at the Department of Engineering website <http://www.eng.au.dk>.

Publisher: Aarhus University©

URL: <http://www.eng.au.dk>

Year of publication: 2017 Pages: 86

Editing completed: March 2017

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Keywords: Building Information Modeling (BIM); Sustainability; Indoor Environment, Performance Analysis; Indoor Air Quality; Thermal comfort; Moisture comfort; Acoustic comfort; Lighting comfort; Energy efficiency

Supervisor: Prof. Poul Henning Kirkegaard; Aliakbar Kamari

Financial support: No external financial support

Please cite as: Poul Henning Kirkegaard, Aliakbar Kamari (Eds), 2017. BUILDING INFORMATION MODELING (BIM) for Indoor Environmental Performance Analysis. Department of Engineering, Aarhus University, Denmark. 86 pp. - Technical report CAE -TR-3

Cover image: Aliakbar Kamari

ISSN 2246-0942

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Abstract

The report is a part of a research assignment carried out by students in the 5ETCS course "Project Byggeri - [entitled as: Building Information Modeling (BIM) - Modeling & Analysis]", during the 3rd semester of master degree in Civil and Architectural Engineering, Department of Engineering, Aarhus University. This includes seven papers describing BIM for Sustainability, concentrating specifically on individual topics regarding to Indoor Environment Performance Analysis.

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I

Building Information Modeling for Indoor Environmental Performance Analysis – Indoor Air Quality

Christian Skaarup Laustsen

Abstract

The purpose of the present study was to review how BIM could be applied for Indoor Air Quality (IAQ) performance analysis with Autodesk Revit 2017 as the BIM software. Hereby, showcase some of the possibilities BIM as a methodology provided by explaining and discussing selected software applications. The review showed, extraction of building information directly from Revit as a single modelling software for various performance analysis was obtainable. Hereby, the application of BIM can provide a more holistic process between architectural design development and indoor environmental performance as a more efficient workflow for detailed designing can be implemented earlier in the design process. The review also showed that, for IAQ performance analysis with Revit, some software applications discussed lacked implementation of the BIM methodology, as the transaction of information was limited to CAD geometries. However, the explained and discussed software applications for analyzing the performance of IAQ were overall adequate because of the building information level of a Revit-model. Nonetheless, defining a common information transactional process and practical strategies for integrate BIM in IAQ performance analysis to achieve comfortable indoor environment and a sustainable development could be a further advancement, as the current limitation hinders the complete implementation of BIM.

Key words

BIM, Indoor Environment, Performance Analysis, Sustainability, Indoor Air Quality

1. Introduction to BIM and Sustainability

In general, sustainability is a strategic mentality of focusing on finding the balance of what will satisfy humanities modern needs and the need of protecting the environments which constitute our planet [1]. However, the strategic mentality of the term sustainable development is not just about protecting the environment. A well acknowledged definition of sustainable development was presented by the *United Nations World Commission on the Environment and Development* [2] [3]:

“Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs.”

Chapter 2, Section IV, Our Common Future (1989)

Hereby, sustainable development is about bringing an innovative mindset into humanity’s modern existence. This mindset has led to the three major pillars of the modern term definition; *economic development*, *social development* and *environmental protection* [1]. Thus, making sustainable development a holistic mentality.

In the latest years, a much stronger focus on sustainable development in the building industry has become mainstream in the developed world [4] [5]. This is a result of increased knowledge of its potential and restricted demands from governments. Especially, the European Union (EU) has made more restricted demands on the total energy use and hereby indirectly the use of resources [6]. A progress which in Denmark is clarified by the development in specifications stated in the national building regulations [7]. These continuously increases in energy demands, which are often combined with ambitious goals for the indoor environment, are challenging [8]. Thus, for a sustainable built strategic principles and requirements which define an integrated approach to the design and evaluation of the environmental, social and economic impacts are needed [9]. Hereby, a great focus is placed on quality performance analyses earlier in the design process. This can only be achieved with good communication between the modelling software and the analysis tools [10].

Likewise, to achieve energy efficient buildings with a good indoor environment a multi-disciplinary design team can be beneficial which complies well with the holistic mentality of sustainable development. With a multi-disciplinary design team, it is possible to better integrate functional and sustainable solutions since all decisions are influenced by architects, engineers, contractors, and building owners [8]. However, a multi-disciplinary design team and thus many project partners working on the building project at the same time, sets greater demand on the communication during the process.

Building information Modelling (BIM) is an emerging methodology in the building industry since it can be used to design, document and analyses building projects. Likewise, BIM can also be used as an enhance communication tool between all project partners [2]. Therefore, BIM is a set of different tools and methods for achieving a common goal. Hence the definition of a methodology [11]. Hereby, BIM meets the requirements of the present, why it has changed the way building designers and consultants work with building projects, since it also can help the building industry in the sustainable development by allowing easier and faster assessment of the strategic framework of efficiency, innovation, and profitability [12].

The advantage of a BIM process is that many types of analysis and simulation can take place as part of the design process, allowing engineers quickly to cycle through iterations and get instant feedback on project performance [10]. Another advantage of a BIM process is that all information can be stored in a cloud-database. Hereby all information is parametric and thereby interconnected, thus making it accessible for all project partners [2]. Therefore, a BIM model can be used holistically throughout the design-to-build-to-own process as any changes to the BIM model are instantly reflected, hereby speeding up the project process [12]. This also makes BIM ideal for design decision making, production of high-quality construction documents, cost estimating, and construction planning [2]. In figure 1 the strength of a BIM process is highlighted by a comparison with the use of a traditional drafting-centric workflow process [10].

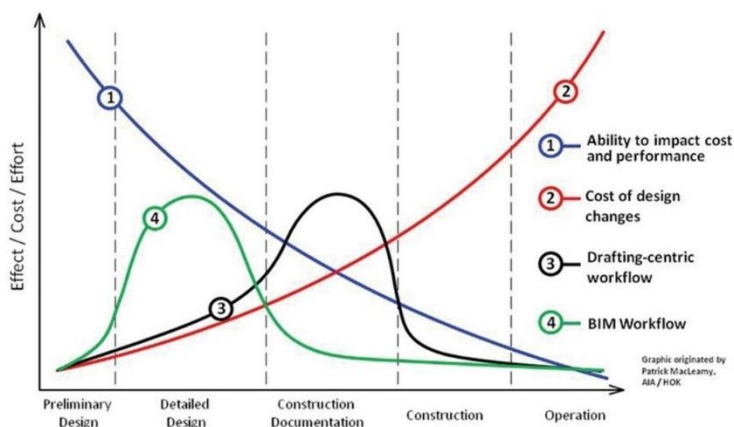


Figure 1: The Patrick MacLeamy Curve for BIM

Based on the work of Patrick MacLeamy, published in the article "What does BIM mean for civil engineers?" by Adam Strafaci

The primary purpose of the present study is to review how BIM can be applied for indoor environmental performance analysis with *Autodesk Revit 2017* as the BIM software. It will explain some of the possibilities BIM as a methodology provides by explaining and discussing selected software applications for indoor environmental parameters. The parameter which will be focused on is *Indoor Air Quality (IAQ)* with *Thermal Comfort* and *Acoustic Comfort* as correlating consideration parameters. Section 2 will explain the application process of applying BIM for indoor environmental performance analysis as well as enlighten the definition of IAQ. Section 3 will explain and discuss BIM software tools for IAQ application. These will be summarised in a table at the end of the section. Finally, a conclusion on the possibilities for analysing IAQ with a BIM-based model by the discussed applications will be stated in section 4.

2. Indoor Environmental Performance

The application process of applying BIM for indoor environmental performance analysis is in general terms highlighted by figure 2. The suggestion of an iteration process, is based on the possibilities an intelligent 3D virtual building model provides by containing all aspects of the building information into an intelligent format that can be used to optimize the building solutions before committing to a design proposal [13]. Meaning after evaluating an initial indoor environmental performance analysis it is possible to modify the building design for performance improvements [14].

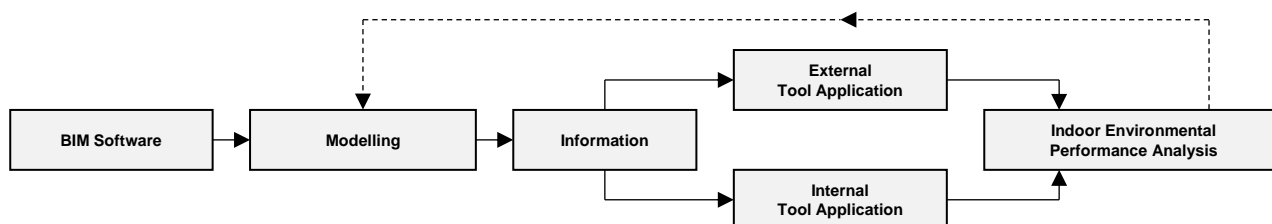


Figure 2: The BIM Workflow for Indoor Environmental Performance Analysis

Based on the presented BIM workflow on ASHARE Building Performance Modeling Conference of 2016 and the paper "Building Information Modeling for Indoor Environmental Performance Analysis" by Yaik-Wah Lim

The performance of the indoor environment is important for both new construction and renovation because the average human has an indoor occupancy time of 90% [15]. Hereby, when spending so much time inside the indoor environment is crucial for the health and wellbeing of the occupants [16]. Likewise, is the indoor environment related to the energy consumptions of buildings, as stated in the introduction. Studies have furthermore shown that the costs of a poorly indoor environment are often higher than the costs of energy used

in the building due to reduced performance from the workers and absenteeism of self-same [15]. Occupants in discomfort are more likely to act on themselves to make a more comfortable environment. For instance, opening windows, turning on radiators etc. This can affect the energy consumption and consequently make the building perform different than expected [15] [17]. Hereby a poorly performance of the indoor environment negatively effects all aspects of a sustainable development. This is the reason why it is important to analyse all parameters of the indoor environment in the design process. Which indoor environmental parameters that should be measured when analysing the performance is overall shown in figure 3 [11]. For each of these parameters a lot of factors must be considered. Likewise, each parameter is correlated in terms of effecting the performance of the indoor environment. However, the impact correlation is not limited to the parameters in figure 3. Façade parameters, room parameters and building objects also have an influence [18].

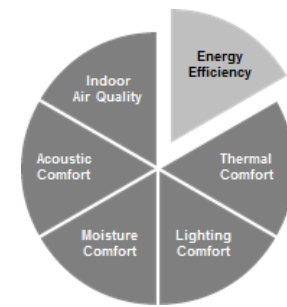


Figure 3: Indoor Environmental Performance Parameters
Based on the work of Aliakbar Kamari

2.1 Indoor Air Quality

Indoor Air Quality refers to the air quality within and around buildings. Especially within as it relates to the health and comfort of the building occupants [19]. It is important to understand and estimate the air physics of the ventilated space to get a good performance for the IAQ [20]. The key is to:

- Insure an adequate airflow rate without draft by controlling the airflow pattern so the air velocities are low.
- Insure the temperature gradients are small.
- Keep a natural air composition in the occupant zone.

Controlling the airflow pattern at an adequate airflow rate so the air velocities are low is generally analysed by considering the layout of air supply and return openings. The performance will often be based on an analysis of the inlet air jets [20]. The jets' airflow can either be in a laminar or turbulent state. In fluid dynamics, laminar flow is the state where the air will flow parallel or streamlined without chaotic changes in pressure and flow velocity. If the flow has chaotic changes in pressure and flow velocity it is considered turbulent [21]. Likewise, is the air inlet jets affected by the thermal conditions in the space. For a cooler horizontal air jet the downstream jet distance will be reduced since cooler air has a denser density than the ambient air why the force of gravity is greater. The opposite principle applies for a warmer horizontal air jet since the density is lower than the ambient air. This must be considered when using ventilation for cooling and or heating [20]. Hereby, IAQ considers thermal comfort as thermal sensation is determined by the temperature of the air and room space surfaces, air velocity, turbulence intensity and relatively humidity [22]. Besides considerations of thermal comfort, IAQ is ensuring that the chemical composition of indoor air is clean and fresh. Meaning avoiding chemical pollutants, particulates, pollen, mildew and unwanted emissions in the air. A low chemical composition is obtained by supplying fresh outside air. If the air is too polluted or is stale, it can make people uncomfortable, unproductive, unhappy, and sick. Fresh air helps people be alert, productive, healthy, and happy [23] [24]. In others words in comfort. The indoor air becomes stale when CO₂ concentrations are too high which in indoor environmental building settings is due to human respirations [25].

The airflow rate for IAQ can either be supplied by using natural ventilation such as operable windows and skylights, by mechanical ventilation, or as a combined service type called hybrid ventilation [20] [25]. The use of mechanical ventilation or generally by increasing the performance of IAQ by using more outside air, usually increases the building's energy use [25].

3. BIM for Indoor Air Quality

The key factors, stated in section 2.1, can be examined by indoor performance analyses. The possibilities with BIM and *Revit* as the software will be explained and discussed in the following section. It will be limited to mechanical ventilation for IAQ as it is considered to assess more parameters of the showcased in figure 3.

3.1 Airflow Rate

This subsection will consider some of the possibilities of assessing the needed airflow rate for achieving comfortable IAQ with a *Revit*-model.

3.1.1 Integrated Revit Tool

To determine the needed airflow rate for thermal and cooling loads it is possible to use an integrated *Revit* tool. It is a part of *Autodesk's* Mechanical, Electrical and Plumbing (MEP) engineering tools for *Revit* [26]. The tool can be found in the analyze tab in the interface. Spaces must have been placed in the *Revit*-model to use the tool. Likewise, prerequisites for the building or space(s); *type, location, infiltration class, service type and project phase*, must be stated. This is done in the tool window [27]. The prerequisites are used for a quick setup of various thermal loads in terms for the use and estimating the impact of the outdoor climate. Hereafter, set points for the comfort in terms of thermal sensation, relative humidity and needed airflow rate for removing emissions and pollutants from the indoor air are stated. Suggested comfort set point for the necessary airflow rate for removing emissions and pollutants is not provided by the tool, why the value must have been determined beforehand. When all information is entered, the calculation can be run. The result is a rapport where the load quantities and the needed airflow rate are listed in a table [28].

Discussion

For a comprehensive conceptual evaluation of the needed airflow rate for comfortable IAQ the tool provides a quick and decent evolution. Especially, in terms of thermal IAQ comfort. Likewise, the quickness of the tool provides the possibility of evolution many different ventilation control systems rapidly as the heat or cooling service type. This possibility can be helpful for selecting the most sustainable solution early in the design process. However, the ventilation control systems which can be selected are limited and cannot be edited (reservations for licensing) [29]. Nor are many of the settings accessible, why a critical review of the calculation is not possible when using the integrated tool. This is criticizable for an evolution of the analysis results showcased in the report. The thermal analysis properties are editable and/or accessible. The reason is that the integrated tool is primarily for thermal comfort evolution. Nonetheless, the requirement for establishing a set point for the airflow rate, which is needed for emission and pollutants removal, beforehand makes it necessary to conduct a review of the demands for the building and space(s). This review can be based on various standards from *ASHARE, AIA, ISO, Danish Standards* etc. However, this does not utilize the possibilities a BIM-model provides as an intelligent 3D virtual building model comprehensively. By improving the utilizing of all the BIM prerequisites by implementing emission and pollutant loads as analysis properties, as it is the case for the thermal properties, a more valid assessment of all comfort criteria's can be made. However, the building information level of a *Revit*-model makes it to some extent possible to estimate additional airflow rates with some effort. This is explained and discussed in section 3.1.2.

In the integrated tool the weather data is associated with the location entering by data importation from the *NCDC* and nearby weather stations. This is general for *Autodesk's* building performance analysis tools [30]. For instance, in Denmark it is in the building regulations stated that specific weather data must be used when applying results from building analysis software as documentation for thermal comfort [7]. Hereby, the airflow rates determined by the tool may not be used in Denmark as documentation for the thermal performance and thus the performance of IAQ to some extent. A commonly used software tool for modelling and performance documentation in Denmark is *BSim*. It is used for analysing buildings and installations. *BSim* includes a collection of advanced tools for simulating and calculating. It is developed by the *Danish Building Research Institute* [31]. A thesis study has researched how to export information from a *Revit*-model to *Excel* via *Autodesk Dynamo*, formatted in a *BSim* compatible schedule, to allow automation of energy simulations. By stated it was succeeded, why *BSim* to some extent is compatible with *Revit* [32]. *BSim* provides, as an independent software, the possibility of implementing CAD models for geometry modelling [33]. Likewise, *BSim's* compatibility with BIM software is an ongoing research area [34].

3.1.2 Scheduling Information by Revit as BIM Software

For determining the needed airflow rate for removal of emissions and pollutants it is possible to use a schedule (information table) by a formula function where existing model information is used as input data or settings for the calculation. Which information should be showcased in the table-fields of the schedule must initially be selected. Which one(s) to select depends on the formula(s). Which formula(s) to use, can be based on the review findings in various standards. To make a formula parameter use the "fx"-button in the schedule

properties. When the formula is added, the calculation results will be displayed in a new table-field [35]. A limitation of the formula function in *Revit* is that it cannot evaluate string values. It can only evaluate numbers and units [36]. Therefore, it is necessary to assign a room-type-number by default. This function is possible by external software's like *Microsoft Excel*. A schedule can be exported to *Excel* [37]. The use of *Excel* will not be discussed in this study, but the option makes it possible to change any building information extracted. However, updated information will not be synchronized with the *Revit*-model. Hereby, downgrading the BIM compatibility.

Discussion

The use of schedule and hereby the high level of building information in a *Revit*-model is one of the strengths of BIM as highlighted in section 1 and 2. The software limitation of the possibilities with formula is shortage as a comprehensive function. However, what is possible is useful for implementing for example engineering calculation, as known in the industry from *Excel*. Likewise, for clarification, the formula function is not limited to airflow calculations why there are many options with the function.

The research for the formula functions also showcased an additional point of discussion for the integrated tool described in section 3.1.1. In various standards, many recommend values are based on the number of occupants when accessing emission and pollutants from humans. As described in section 3.1.1, the settings for the analytical results were not accessible why a critical review was not possible directly in the integrated tool. However, by displaying the quantity of occupants assigned to the room by the tool in a schedule it was displayed as a decimal number. By estimating the occupants loads by a decimal number it can be argued that the analysis does not consider a worst-case scenario. Thus, diverting from the genuine performance of the indoor environment. However, the formula function in schedule provides the possibility to roundup numbers, but is another limitation of the usefulness of the integrated tool.

3.2 Indoor Air Physics

This section will consider some of the possibilities of assessing the air physics of the comfort zone of the occupants with a *Revit*-model.

3.2.1 LindQST Through MagiCAD

LindQST is as a web-based *Revit* plugin-tool by *Lindab* through *MagiCAD*. *QST* stand for "Quick Selection Tool". The tool contains selecting, calculation and visualization of *Lindab*'s products. It can likewise be used as a documentation-finder for the various products. Hereby, multiple possibilities. For analysis of BIM for IAQ the most essential tool application is *Indoor Climate Designer*. The application is used for analysis and visualization of how selected diffusers and their arrangement affects the indoor environment of a space in terms of air distribution, acoustics and non-isothermal conditions. The selection of diffusers is based on the needed airflow rate, room space type and ventilation service type. This preconditions likewise prescribes the indoor environmental demands. All settings are however editable. After analysing the mechanical ventilation setup, the results are graphically shown and the diffusers can be imported to *Revit* as CAD files with dimensional properties [38]. It is currently not possible to export nor import room spaces to the tool.

MagiCAD for *Revit* is a BIM solution for MEP designing. *MagiCAD* enables drawing and calculations making the design of accurate BIM models and user-configurable printouts easier, more flexible and less time-consuming. The company collaborates with leading international manufacturers, by providing plugin-tools like *LindQST*. Hereby, other company plugin-tools can be download to *MagiCAD* for various applications [39]. See section 3.3.2.

Discussion

The quick assessment of how diffusers affect a space is an efficient evaluation which follows simplified yet accepted theory used in the Danish engineering industry. More on this theory can be found in *Lindab*'s theory guides or *DANVAK*'s scientific literature [22] [40]. It is unknown if the simplified methods are as common in the international industry as in the Danish industry. However, *LindQST* is accessible in various languages as well as *Lindab*'s theory guides can be found in English [41]. That it is possible to evaluate the distribution of air, the acoustics and non-isothermal conditions makes it a holistic tool which complies well with the stated in section 2. Combined with the quickness, the tool is well fitted for reflecting on the performance of IAQ during the early detailed design process. The compatibility with BIM by the possibility of importing diffusers with airflow

properties to *Revit* is an additional strong feature. However, the lack of space incorporation is a major shortage for the tool. But, the tool is also available for *Autodesk AutoCAD* where spaces with or without diffusers can be imported or exported to and from the tool [42]. So, it is an advantageous BIM-option *Lindab* is aware of. Implying that it is an upcoming function for the *Revit* plugin.

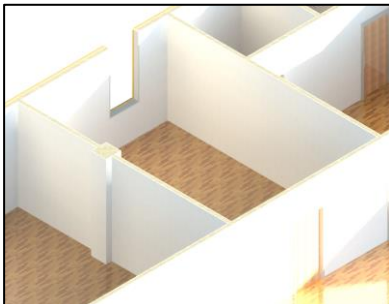
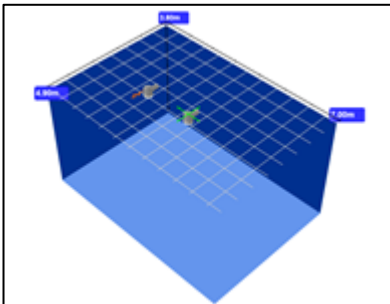
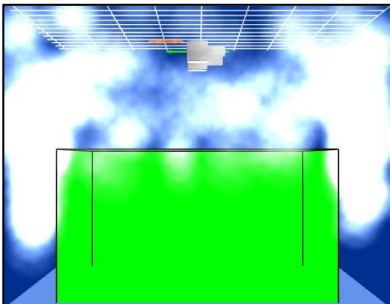
That it is only possible to analyse *Lindab's* own diffusers is adverse, but an expected limitation. It can be assessed by using the comprehensive information level BIM modelling provides as design criteria's. Another limitation, is the efficiency of selecting products. Since the tool is web-based, products are not preloaded. The loading of products can make the tool crash. The advantage of the web-based tool is that projects can be accessible by any hardware with a network-connection making the tool in accordance with the BIM methodology.


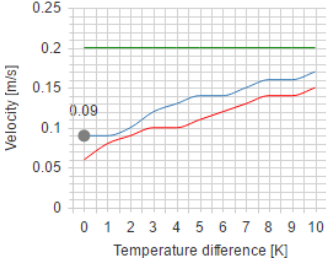
Example

The following example is based on a model done in the course “*Building Information Modelling - Modelling and Analysis*” at Aarhus University Department of Engineering in the spring of 2017.

Table 1: Example of a Performance Analysis with LindQST

Room Information						
Room type:	Office	-	Occupants: *	2 per.	Height:	3.8 m
Length:	7.0 m		Width:	4.9 m	Area:	34.3 m ²
Demand 1: **	20 L/s pr. per.		Demand 2: **	0.7 L/s pr. m ²	Airflow Rate:	64 L/s

Model in Revit	Model in LindQST	Analysis
		

Analysis Results				Imported to Revit												
Settings Suspend ceiling: No Diffuser(s): LCS-160 Ceiling offset: 0.3 m Conditions: Isothermal																
Occupant Zone <table border="1"> <thead> <tr> <th>ID</th> <th>Demand</th> <th>Result</th> <th></th> </tr> </thead> <tbody> <tr> <td>Velocity</td> <td>0.2 m/s</td> <td>0.1 m/s</td> <td>✓</td> </tr> <tr> <td>Sound</td> <td>35 dB(A)</td> <td>32 dB(A)</td> <td>✓</td> </tr> </tbody> </table>					ID	Demand	Result		Velocity	0.2 m/s	0.1 m/s	✓	Sound	35 dB(A)	32 dB(A)	✓
ID	Demand	Result														
Velocity	0.2 m/s	0.1 m/s	✓													
Sound	35 dB(A)	32 dB(A)	✓													
Non-Isothermal Conditions Legend: Impulse velocity (blue), Thermal velocity (red), Required velocity (green), Max velocity (grey) 																

* Based on *Revit* prerequisites. Rounded from 1.7.
 ** Suggested values.

3.2.2 Autodesk CFD

For detailed analysis of the room air physics the *Autodesk* software *Autodesk CFD* provides computational fluid dynamics (CFD) and thermal simulation for analysing airflow patterns and temperature distribution inside and outside buildings. Hereby, the software can help to improve IAQ by optimizing HVAC installation designs, validate airflow behaviour and reduces energy consumptions. This is possible, as the software can solve the

complexity of heat and fluid transfer related to buildings and hereby confine miscalculations or judgement errors [43]. The software is a CAD-integrated software since it can only be used by importing a model from software's like *Revit* [44]. This can however be done easily in *Revit* by adding a software connecting and thus creating an integration within the modelling platform. Otherwise, it is also possible to export the *Revit* geometry in a SAT file format [45]. Likewise, with *Autodesk's* cloud-based solver it is possible to use the software with less powerful hardware [46].

Discussion

The complexity of a CFD application requires a profound understanding of how heat and fluid transfer interact in a building environment and understand the correlating with IAQ. Hereby, CFD software should only be used by experts with proper knowledge. Especially, when dealing with turbulence modelling. Turbulence occurs in mixing ventilation which is frequently used for comfort.

If the right properties or solving models are not assigned the results from a CFD-software can be very misleading. Hereby, the complexity of the software calculation engine is vital to get precise results. The precision of *Autodesk CFD* is discussed in section 3.2.3 by a comparison with *ANSYS Workbench*.

The possibility for quick exportation of the *Revit*-model is a strong feature for BIM implementation. Particularly, as *Revit*-models imported to *Autodesk CFD* have some properties recycled. Otherwise it just a shell. Hereby, properties must be reassigned.

However, when testing the possibility on a detailed *Revit*-model, information was lost. When testing the software on a simple *Revit*-model, the transaction was acceptable. This highlights that when doing CFD-analysis it is important to consider which information is important for the analysis. For the present study, it is building performance analysis for IAQ. In this case when looking at the indoor environment it could be beneficial to export data on a room based level. For analysis of the flow around the building, perhaps only the building envelope should be exported. The lesser information the faster the analysis process.

The possibility of a cloud-based solving is likewise a strong feature, but the need of a network connection can at times effect the functionality. Nonetheless, any CFD-software requires robust hardware because of the complex mathematics for describing the physics. The strength of the complexity is that the analysis results can be very detailed and hereby insuring the IAQ.

3.2.3 ANSYS Workbench - Fluent

ANSYS Workbench is a simulation software packages. It can simulate multiphysics conditions by the comprehensive and integrated applications [47]. Hereby, leveraging common and compatible data models. The advanced engineering simulation technology allows its users to simulate the interaction between structural mechanics, heat transfer, fluid dynamics, acoustics and electromagnetics all within a single unified simulation environment by stated [48]. Thus, it provides multidisciplinary simulations. Likewise, the software can communicate with many of the major CAD systems by geometry importation, enabling a more efficient design process [47]. Consequently, the software and its applications can conduct any analysis that *Autodesk CFD* can and much more. For example, analyse of the perceived indoor quality in terms of air composition [49]. The comparable application of *Autodesk CFD* in *ANSYS Workbench* is called *Fluent*. The advanced technology of the software sets demands on the hardware, but depends on the application.

Discussion

The CFD interface of *Fluent* in *ANSYS Workbench* is similar to *Autodesk CFD*, why the use of the software should be done in accordance with the discussed in 3.2.2. In terms of IAQ the possibilities are very similar and both software's are qualitatively to compute IAQ analyses by stated from the companies. *Autodesk CFD* is however best when addressing the most common simulation analyses as it is a CFD software marketed to designers who primarily solve steady-state analyses for graphics output for architectural presentations [50]. The advanced technology of *ANSYS Workbench* and the multidisciplinary options is good when accessing multifaceted analyses for performance and comfort validation. Which software to use depends on ownership costs, usability and the performance analysis needed. However, by a survey on preferred CFD software packages from 2016, 77 persons preferred *Fluent* and 16 *Autodesk CFD* of a total 289 answers. The precision of *Fluent* is likewise highlighted by a quantitative comparisons of results obtained from various CFD software packages [44] [50].

Generally, the application of CFD has in the building industry been limited to the schematic design phase due to the complexity, compared to tools like *LindQST*. Future research could be an investigation of the possibilities of connecting BIM design variables at the early design phase and the computational data needed to utilize CFD for development in the architectural design process. Hereby, CFD can become a more integrated and innovative application [51]. That *Autodesk CFD* can be integrated with *Revit* is a function which computes well with this statement. However, CFD simulations will still require adequate knowledge. For now, the large amounts of input data required for CFD simulations, still make the software's most applicable late in the detailed design phase. Nonetheless, time and resources needed will be decreased with the advancement of more powerful hardware and hopefully future BIM implementations.

3.3 Ventilation System

This section will shortly consider some of the possibilities of assessing the ventilation system which distributes the air, hereby insuring the IAQ.

3.3.1 Integrated Revit Tool

When space layouts are complete and an acceptable performance of IAQ is analysed, the ventilation system, compiled by a duct system, can be sized. This is important for IAQ since the ventilation system distributes the air to the diffusers which ensures the quality when using mechanical ventilation. Sizing of ducts by either maximum air velocity or pressure loss can be done by an integrated *Revit* MEP tool [52]. The tool can be found in the analyze tab in the interface. The sizing is based on the airflow rates assigned to the diffusers imported to *Revit* from example *LindQST*. The air velocity is important for the acoustic comfort as the air pressure within the duct system creates sound. The airflow rate is created by the electric powered fans in the air handling unit overcomes the system pressure loss [22]. So, minimizing the pressure loss in the system improves the energy efficiency. The sizing is done in compliance with prevalent mathematical formulas and estimation of pressure loss from fittings is evaluated in compliance with the acknowledged *HVAC ASHRAE Duct Fitting Database* [53]. *MagiCAD* as a BIM software packages provides a similar tool [39].

When designing a duct system in *Revit* it is best to use a “*mechanical template*” as it assigns MEP prerequisites to the *Revit*-model or create a new template with adequate settings. Various templates insure the best settings for the project partners discipline [54]. This is a strong application when multiple users work on different parts of the *Revit*-model [55]. This highlights *Revit* as a collaboration software as well as a modelling software.

3.3.2 SystemairCAD Through MagiCAD

It is likewise possible to import an air handling unit into *Revit*. This is possible because some manufactures have made CAD models of their units. A such manufacture is for example *System Air*. By their calculation software *SystemairCAD* an air handling unit can be sized an exported to *Revit* or directly in *Revit* by the related *MagiCAD* plugin. The plugin, however requires the software to be installed. More information on the software can be found on the manufacture's homepage [56].

3.4 Summary

The following table is based on the stated in referred literature or subjective evaluations. Only the main explained and discussed software applications is included. They are ranked from 1-10, were 10 is the best score.

Table 2: Summary of the Software Tool Applications

Software	Revit and BIM			Indoor Air Quality Evaluation					Analysis			Other Performance Parameters Considered					Other	
	Import Data to Revit	Export Data from Revit	Integrated in Revit	Information Flow	Overall Air Distribution	Detailed Flow Pattern	Non-isothermal Considerations	Heat Transfer	Chemical Air Composition	Quality	Speed	Customization	Thermal Comfort	Moisture Comfort	Acoustic Comfort	Lighting Comfort	Energy Efficiency	Hardware Requirements
Heat and Cooling Loads			✓	8	✓		✓			6	8	5	✓	(✓)		✓	*	8
Revit Scheduling			✓	9	?	?	?	?		?	9	8	?	?	?	?	*	6
LindQST	✓	(?)	(✓)	6	✓	(✓)	✓			7	7	7	✓			(✓)	9	8
Autodesk CFD		✓	(✓)	7	✓	✓	✓	✓	(✓)	9	6	7	✓	(✓)	(✓)	✓	7	7
ANSYS Workbench Fluent		(✓)		4	✓	✓	✓	✓	✓	10	4	8	✓	✓	✓	✓	5	7
Revit Duct System			✓	8	✓					8	9	6				✓	*	6
Systemair-CAD	(✓)	(✓)	(✓)	7	✓					7	7	4				✓	8	7

? Unknown / Not Specified

() Limited

* Incorporated in Revit

4. Conclusion

The purpose of the present study was to review how BIM could be applied for Indoor Air Quality (IAQ) performance analysis with *Autodesk Revit 2017* as the BIM software. Hereby, showcase some of the possibilities BIM as a methodology provided by explaining and discussing selected software applications.

The review showed, extraction of building information directly from *Revit* as a single modelling software for various performance analysis was obtainable. Hereby, the application of BIM can provide a more holistic process between architectural design development and indoor environmental performance as a more efficient workflow for detailed designing can be implemented earlier in the process. Subsequently, applying the methodology of BIM in a design process could be beneficial for achieving a sustainable built environment.

However, the review also showed that, for IAQ performance analysis with *Revit*, some software applications discussed lacked implementation of the BIM methodology, as the transaction of information was limited to CAD geometries. Thus, they only aided the design process by geometry sharing. A notable software with this limitation was *ANSYS Workbench Fluent*. BIM-based performance analysis can be defined as much more, as BIM potentially provides a broader level of information sharing between applications. The discussed software applications from *Autodesk* provided a broad level of information sharing to and from *Revit*, which was expected as *Revit* is an *Autodesk* modelling software and BIM implementation is a company philosophy.

Nonetheless, the explained and discussed software applications for analysing the performance of IAQ by the virtue of BIM were overall adequate. The integrated *Revit* tool for heating and cooling loads evaluation together with common airflow calculations, made easier by information tables, can after architectural designing determine IAQ criteria for software's like *LindQST*. *LindQST* can hereby in the early design process make comprehensive conceptual evaluations of the room air distribution which late in the detailed design phase can be confirmed by CFD software's like *Autodesk CFD* or *ANSYS Workbench Fluent*. Likewise, it is possible to competently size the duct system by an integrated *Revit* tool and other application plugins. That *LindQST* can import diffusers with dimensional properties to *Revit* makes the sizing quicker. This additional give the possibility of applying the needed power supply in an energy analysis and compute complete schedules for

the needed materials of the ventilation system since all information is stored in the BIM-model. As any changes to the BIM-model are instantly reflected for all project partners, an overall evaluation of the IAQ by the ventilation system throughout the design-to-build-to-own process is possible. However, defining a common information transactional process and practical strategies for integrating BIM in IAQ performance analysis to achieve comfortable indoor environment and a sustainable development could be a further advancement, as the discovered limitation hinders the complete implementation of BIM.

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II

Building Information Modeling for Indoor Environmental Performance Analysis – Thermal Comfort and Indoor Air Quality

Stefan Bæk Jensen

Abstract

As a part of a research project performed by students at Aarhus University, Denmark, available tools for simulating building performance on energy efficiency, thermal comfort, indoor air quality (IAQ), lighting, moisture, and acoustics is investigated. The tools are tested for compatibility with building information modelling (BIM) methodology and are evaluated with their current functions and calculation methods. The tools are furthermore evaluated on their abilities for interactive collaboration and intended or necessary level of detail for performing simulations. This research is focused on thermal comfort and IAQ. Simulations in LindQST, Insight 360, and IAQx has been done to establish an overview of the necessary inputs and thereby determine the required level of detail to perform such calculations without making improbable assumptions. A collaboration between the available tools, not only on building performance, but all aspects of the life cycle of a building is suggested to establish more comprehensive results, leading to improved sustainable solutions.

Key words

BIM, Sustainability, Thermal Comfort, Indoor Air Quality

1. INTRODUCTION

1.1. Sustainability

As a growing number of people started realizing human's impact on the environment in the 1970s among other caused by U.S. Senator, Gaylord Nelson, when he called for an environmental "Earth Day", to be held in the spring of 1970 [1].

Due to the oil crisis and the realization of the environmental changes, a small group of design professionals and building occupants started a "green" building movement which in the 1990s changed to sustainability [1].

Sustainability includes more aspect than the term "green" and it is commonly accepted that sustainability consists of three ground pillars: People, Planet, and Prosperity. The better the three of them balance out, the better design solution[1]. Projects can achieve different stages of sustainability and be rewarded with certifications e.g. LEED.

The World Commission on the Environment and Development may have presented the best definition in the 1987 report to the United Nations: *"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs"* [2].

1.2. Integrated Design Process

A typical project organization diagram is presented in Figure 1.3.1, where it is seen that the owner hires architects and contractors separately, where no contract between the two exists. As an agreement with the owner, the architect and contractor exchange information based on trust and teamwork. Unfortunately, this is not always sufficient, and may cause a "risk gab" between the architect and contractor. Instead Patrick MacLeamy suggest, what he call Buildingsmart organization model [3]. See Figure 1.2.2. Where the involved parts, are bound by a single contract, which ensures the teamwork as information, risk and rewards are shared.

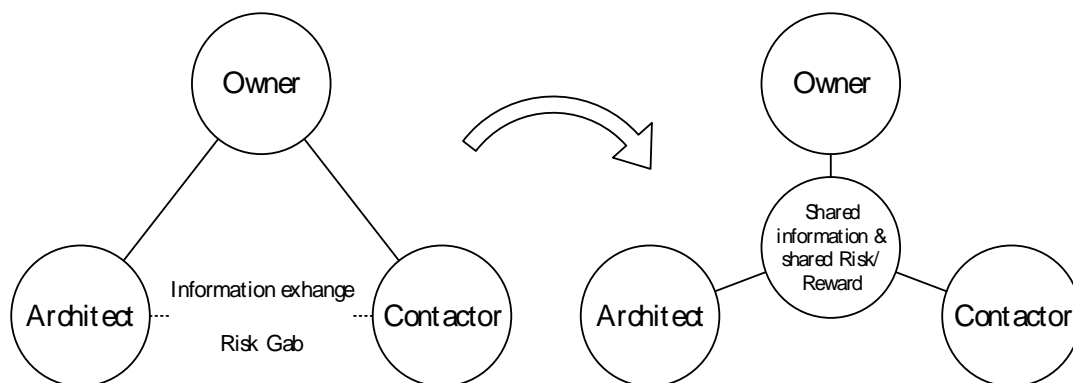


Figure 1.2.1 Typical project organization diagram.
Source Patrick MacLeamy - HOK

Figure 1.2.2 Building smart organization model.
Source Patrick MacLeamy – HOK

This combined contract enables the included parts of a project, to initiate a closer collaboration, resulting in better designed projects. A methodology to perform such projects, could be to use BIM. When using BIM, the involved parts have a shared platform to distribute knowledge independently. This methodology decreases information loss. Besides, this allows designers to shift their effort into earlier project phases[3], where cost of change is low and the ability to change design is high.

This shift in design effort has great economic benefits with potential saving up 30% [3], as a greater detail level, can be established earlier in the typical project phases. See Figure 1.2.3. By increasing the level of detail (LOD) in early phases, more comprehensive simulations and calculations of the building performance is possible [4].

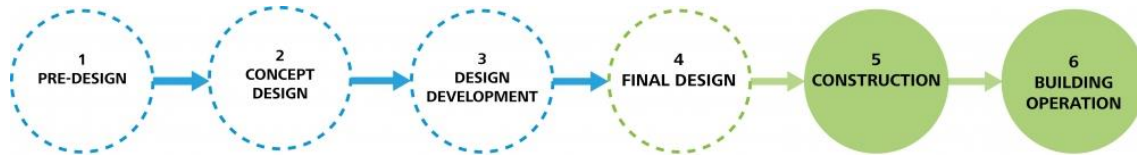


Figure 1.2.3 Typical design process of buildings. Source [4]

1.3. Building Information Modelling

Building modelling has been under development, starting from the historic “Sketchpad” by Ivan Sutherland in 1963 [5]. Which lead to the conventional CAD systems, available in various formats.

As the detail level in the models increased along with the available computer development. So, did the idea for corporation using the software modelling. Different names for this methodology has been suggested by different organizations and researchers [6], but is now widely recognized as BIM.

BIM is sometimes referred to as Building information– model or management. Building information model can be illustrated as in

Figure 1.3.1. Where models previously, have been developed repeatedly by the different stakeholders, but is now combined in a shared model with shared information.

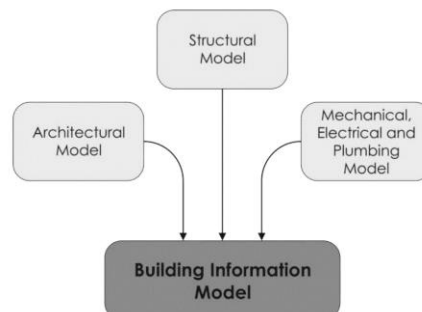


Figure 1.3.1 Building Information Model Structure. Source Kalinichuk (2015) [7]

The framework of BIM was first established by Bilal Succar et al. where the BIM interactions between the stakeholders in a project are described as push-pull knowledge transactions between the fields of policy, technology, and process. Meaning that the included fields adds and extract information from the same model at any time.

Some literature sources describe BIM as: *“BIM is a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's lifecycle”* [8].

2. BUILDING PERFORMANCE PARAMTERS

The European Standard presents three indoor climate classes in the thermal environment, IAQ, humidity, and lighting [9]. As this paper is limited to thermal comfort, and IAQ, only they will be described here.

2.1. Thermal Comfort

Thermal comfort was first investigated as a part of the American military [10]. It was later investigated by Povl Ole Fanger (1934-2006), who published the article “*Calculation of Thermal Comfort: Introduction of a basic comfort equation*” [11]. His calculation includes the main influences on the thermal comfort which are: metabolic rate, clothing, air temperature, mean radiant temperature, air velocity, and relative humidity. Besides, psychological subjective parameters may also affect the thermal comfort [12].

In 1970 Fanger published the book “*Thermal comfort*” [13], where he introduced the term predicted mean vote (PMV), which is assumed as the average thermal sensation of the occupants, which he found never to be neutral for all. This study was carried out in climate chambers, where participants gave their vote of the thermal comfort level in different conditions. Contrary another method for describing thermal comfort is called “The Adaptive Model” and is based upon the occupants’ responsibility for their own comfort. The model is based upon hundreds of field studies where the occupants dynamically interact with the environment, by changing their clothing, adjusting operable windows, shades, or fans [12], [14].

The adaptive approach is recommended in buildings without mechanical ventilation and cooling systems. It is calculated by the operative temperature and the outside temperature with three deviation, defining three comfort classes [9].

Thermal comfort is in Denmark evaluated in four categories: I, II, III, and “out of category” cf. EN 15251 [9]. The Danish Building Regulations guidelines states that building clients determine the restrictions of the thermal environment. In dwelling the guidelines states that the operative temperature outside heating season should not exceed 27°C and 28°C more than respectably 100 and 25 hours [15].

When determine the thermal comfort, it is not enough to find the air temperature, the mean radiant temperature must be included, leading to the operative temperature [16]. Regardless of which model used for determine the thermal comfort.

2.2. Indoor Air Quality

IAQ is depending on the outside air, the loads on the indoor air, and the air change rate [9]. The air quality is perceived by the nose, besides chemical senses in the mucous membranes in the nasal cavities and eyes. The perceived air quality can be expressed by the percentage dissatisfied (PD) or decipol (dp). The strength of most indoor pollution sources can be expressed in olfs, which is pollution caused by a standard person [17].

The building client decides the intended IAQ category either based on the PD or a determined ventilation rate. However, institutions and teaching environment are in Denmark regulated regarding ventilation rates, and offices are included in the restrictions in building class 2020 [18], [19].

When people are the main pollution source, the air quality can be measured by the average CO₂ concentration in air samples or the by measuring the CO₂ concentration in the exhaust air [9].

Currently there is no general agreement how to on how different emission affecting the IAQ should be added together. However, EN 15251 presents three methods to clarify the issue. E.g. by calculating the required ventilation based on people load, and then add the load from

building components, calculate the required ventilation rate per person or floor area, or calculating the required ventilation rate based upon a mass balance between the CO₂ loads and required CO₂ concentration [9].

3. APPLICATIONS

This section will list a selection of available tools for simulating thermal comfort and the IAQ.

3.1. LindQST

LindQST is an application developed by Lindab which is a ventilation duct company. Issues often arise when projecting ventilation ducts, as they are quite large, and difficult to optimize upon in the design phase of a project. Therefore, Lindab has developed an automatic dimensioning of ceiling fixtures. The occupied zone, can then be tested for discomfort regarding draught issues, and to ensure a turbulent mixture of the exhaust air when using mechanical ventilation.

This simulation tool makes it possible to optimize the position of ceiling fixtures earlier in the conceptual design phase. As Lindab has also developed a plugin to Revit, which can take the geometry directly from the drawing into the simulation tool.

Some room specification can be applied from the Revit file, or be stated when preparing the simulation model. Such as model geometry, ventilation supply criteria, boundary condition for thermal- and velocity conditions for the room. Therefore, as much other BIM related software, the more information added to the model early, will decrease the later work load in the project, which will move some of the work load into the early design phase where changes are easier and cheaper.

A simulation is tested for evaluating the results. In Figure 3.1.1. the exhaust air from the ceiling fixtures are illustrated at zero air supply and maximum air supply.

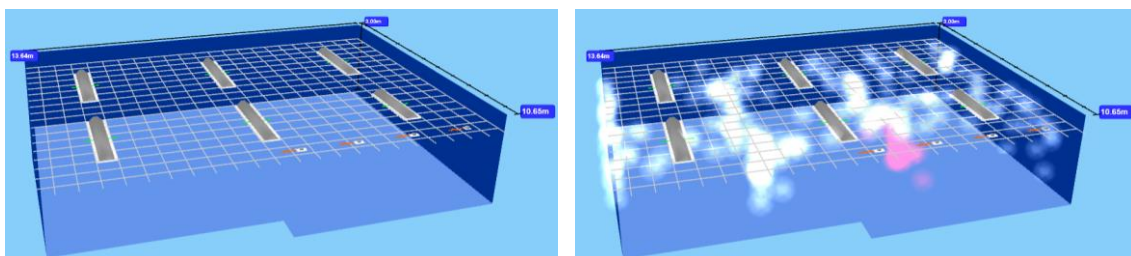


Figure 3.1.1 LindQST simulation of ventilation exhaust distribution in office.

The velocity of the air supply is in Figure 3.1.1 illustrated with a pink colour, as it reaches a critical level in the occupied zone. This result can be extracted as air velocity and used for thermal comfort calculations, or used to defining the occupied zone. Besides, rearranging the ceiling fixtures to prevent critical velocities.

Next step of the development of this tool could be for the software to place the ventilation ducts in a reasonable manner, which could minimize the duct lengths, and prevents crossovers. The ceiling fixtures, could be placed based on simulations like LindQST to ensure an acceptable mixture of air supply without reaching discomfort caused by draught. If an optimization algorithm was applied for placing the ceiling fixtures, another optimization algorithm could be performed for projecting the ventilation ducts.

3.2. IES

IES-VE is an all-around simulation company, and has developed simulation tools for virtually all building phases [20].

As a part of IES-VE, an indoor condition simulation tool has been developed called MicroFlo. By running what they call ApacheSim, it is possible to establish surface boundary conditions for any room modelled. Afterwards loads can be added to the room, and a simulation is now able to run. ApacheSim is able to establish boundary conditions such as air temperature, moisture surface temperatures, mass flows and convective room gains [21]. Afterwards CFD component can be added to the model.

Depending on the detail level of the current project phase, the calculation time can be adjusted by the grid size of the simulation, and the fluid dynamic settings.

With the boundary conditions found by ApacheSim and manually inserted inputs. MicroFlo simulates the air flow temperature, directions and velocity, an example of simulation results is presented in Figure 3.2.1.

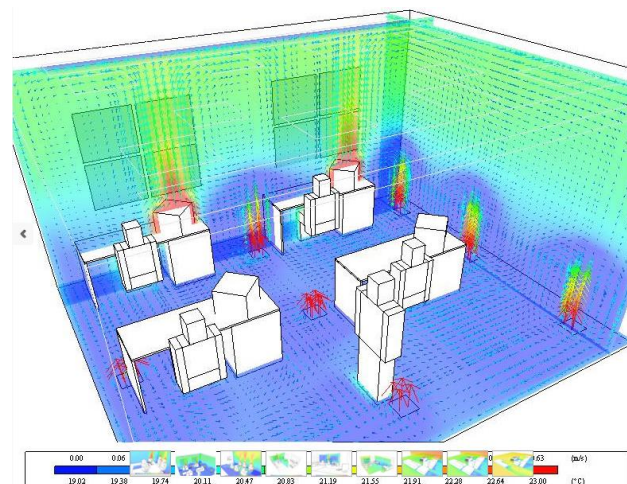


Figure 3.2.1 Microflo simulation result example. Source [21]

As IES is such a large software developer, the interactions between their tools could be enough to establish knowledge of most building aspects thought the buildings life cycle.

3.3. ANSYS, Star CCM+ and XFlow

Both ANSYS and XFlow, are CFD simulation tools, based in fluid dynamic methods. The fluid dynamics of the air can be used for simulating the air movement from the mechanical air supply, the air exchange between indoor and outdoor, or between different zones.

To perform these simulations, the boundary conditions of ambient- and supply temperature, and the air- velocity and directions are necessary.

The simulation will then be able to predict the air movement in the defined zones, and an acceptable mixture, without compromising the comfort in the occupied zone.

Such simulations could be performed by one of these applications, but similar simulations could be performed by LindQST, who also introduce BIM products for the solution. Both ANSYS and XFlow seems to be more used for vehicle aerodynamics. LindQST is however, favouring their own components when performing the simulations.

3.4. IAQx

IAQx differs from the other applications in this paper, as IAQx focuses only on the volatile organic compounds (VOC) which may show to be a crucial factor when predicting the IAQ. However, the ventilation rate is rarely determined by the VOC concentration.

If the standards in the area are to be followed, the thermal comfort often decides the ventilation rate, which then decides the IAQ, as more ventilation will improve the IAQ. If the VOC concentration should be the decisive attribute, the people load must not be the dimensioning factor. Meaning the building is not fully occupied or the VOC load exceeds the CO₂ load. Which could be the case in newly operational buildings.

IAQx calculates the VOC concentration using a first-order decay calculation, which includes: emission rate, source area, initial emission factor, decay constant, and time. Resulting in a time depending VOC concentration. Additionally, filters placed differently in the ventilation system can be added to the calculation.

Parameters such as source area could be directly extracted from any CAD file. Other parameters are material depending, and could be added to the list of material information in e.g. Revit. Allowing a VOC calculation to be performed directly from a Revit file.

3.5. Green Building Studio

Green Building Studio (GBS) is developed by Autodesk, who also have developed AutoCad and Revit. GBS is an online tool, where the model, which can be a BIM model is uploaded and is simulated online. This allows the users to upload many models, to do a parameter analysis without suffering from computer power. Drawbacks however, is that the simulation may not be optimized per calculation speed, and the simulation time, may vary.

The Revit file equipped with material information such as thermal attributes is primarily simulated according the energy efficiency. The output however states the hourly dry bulb temperature. Which is not enough for establishing the thermal comfort, as the operative temperature is needed. In addition to the dry bulb temperature, the mean radiant temperature from the surfaces in each room could be simulated in GBS, to establish a schedule of the hourly thermal comfort in each room of the model.

GBS simulations can be performed repeatedly parallel to the building design development, to continuously support the design decisions.

3.6. Insight 360

Insight 360 is like GBS developed by Autodesk and is a plugin for Revit. It can simulate heating, cooling and lighting. The inputs are taken directly from the Revit-model, with possibilities for adjusting the zones, and schedule the loads. The simulation is performed online as GBS, with similar pros and cons.

A simple simulation has been performed for reviewing outputs regarding thermal comfort. The output consists of peak heating and cooling loads, which are summarized in a table with all the parameters causing either heating or cooling.

This feature draws attention to the potential issues regarding energy efficiency, and allows the user to adjust the critical parameters early in the conceptual phase. However, hourly operative temperature results are necessary to state anything about the thermal comfort.

3.7. EnergyPlus

Energyplus is a calculation core, used by many other tools to establish an energy simulation from a given geometry. It is also often used as a reference when validating other and newer energy simulation tools.

Fanger's thermal comfort equation is used for describing the predicted PD, and the indoor air quality is established based upon the CO₂ concentration [22].

Energyplus is not directly capable of reading and producing industry foundation classes (IFC) files. However, the CAD geometry from different tools can be converted into Energyplus e.g. by using GBS.

3.8. CBE Thermal Comfort Tool

CBE thermal Comfort Tool is an online available tool developed by Center for Built environment, University of California Berkeley [23]. It is a simple linear calculation following Fanger's thermal comfort equation [11]. The inputs consist of, air temperature, mean radiant temperature, air velocity, relative humidity, metabolic rate, and clothing level.

The tool uses a simple steady state calculation, which is not able to determine whether the conditions comply with the regulations, since an hourly simulation is necessary for this. However, by performing some well-defined assumptions, e.g. for the air velocity, this calculation can easily be added to other simulation tools, and thereby give hourly predictions of the thermal comfort in a chosen dry-year.

E.g. the hourly dry bulb temperature calculated using GBS (added with mean radiant temperature), could be combined with the air velocity in the occupied zone calculated by one of the described CFD tools. To establish a comprehensive result of the thermal comfort in the model.

3.9. IdBuild and Bsim

IdBuild and Bsim both use finite element methods (FEM) to calculate the thermal environment in the building [24], [25]. IdBuild is intended as an early tool, for designing the individual room using parametric variation. Where Bsim traditionally is used, for establishing the thermal climate after most design decisions have been made.

By performing comprehensive simulations in the early design phases, a great amount of assumptions must be made. However, Idbuild is easy used to compare parametric variations, to determine the better solution, where it afterwards can be used for documentation of compliance with the standards.

IdBuild is the only found tool in this research to calculate the IAQ c.f. the European Standard described in section 2.2.

3.10. Overview

To allow different software tools to collaborate, a common file format is necessary which is neutral and open. BuildingSmart has then developed the IFC format, to accommodate the issue. IFC is now widely recognised as the BIM format.

A list of the included software, with calculation functions, required LOD, and IFC compatibility, is listed in Table 3.10.1.

Table 3.10.1 Overview of available tools and functions

	Thermal comfort	Air velocity	IAQ	VOC	LOD*	IFC
LindQST	-	X	-	-	High	-
IES	-	X	-	-	Medium	X
ANSYS	-	X	-	-	Medium	X
IAQx	-	-	-	X	High	-
GBS	-	-	-	-	Low	X
Energyplus	X	-	-	-	Medium	(X)
CBE	X	-	-	-	Low	-
IdBuild	X	-	X	-	Low	-
Bsim	X	X	-	-	Medium	-

*assumed required level of detail for performing calculations in the desired tool
 () partially

4. DISCUSSION

When dealing with comprehensive tools and calculations, the overall purpose of buildings is easily overlooked. Do we build because of an intended temperature between 20-26? No, we build to shield us of from the outdoor environment, to achieve a comfort level higher than outside. Why then focus on temperatures, when the goal is comfort?

As many building performance attributes are compensatory, adjusting the parameters to improve a result will often deteriorate another. Therefore, these tools should not be used individually, as most of them specializes in a single building performance attribute. Some even with a hidden agenda of introducing their products into the project.

Thermal comfort is the reason for heating and cooling in buildings, it might be the most important factor for energy usage in buildings. By reducing the active manners for complying with the thermal comfort, the energy consumption inevitably decreases. Thereby, by understanding the parameters affecting the thermal comfort, complications may be prevented.

Most tools found in this research have included the air temperature, but not the operative temperature, or thermal comfort level. These aspects can however, be manipulated by other means than changing the air temperature, e.g. by changing the air velocity. It would be a small extension to add Fanger's thermal comfort equation to these tools, which may prove advantageous in a larger perspective, than just complying with regulations in the final design phase.

For these tools to survive in the jungle of different tools and functions, they must be compatible with the IFC format. Future standards may demand such functions, to create an overview of the building in all aspects of performance and phases, from predesign to demolishing. Thereby allowing better life cycle analyses (LCA) to be carried out.

Issues regarding indoor environment should be reduced if such standardization of simulation tools was established as documentation for new buildings. When all tools can interrelate by using a shared file format, the combinations of potentials are next to limitless. The project

can continuously be compared with a value map conducted in the predesign phase, resulting in an outcome fulfilling every specification.

As the most important objective of projects often is cost, the interactions between tool when working with BIM simplify the LCA, and thereby the overall cost-calculation of the project. A standardization of a sensitivity analysis depending on the project phase could be included when predicting certain building performances. E.g. if simulating the energy efficiency in the early conceptual phase, could be assigned with a predefined uncertainty, which could be decreased as the design phases progressed, as the number of assumptions will be less. This sensitivity analysis could be applied with the method of Morris or by a Monte Carlo simulation [26].

The IAQ is however, more difficult to address as no agreement for calculating the IAQ has been established in the European standard. Besides, the ventilation rates are often controlled by the thermal environment, or the CO₂ concentration. IAQx allow the user to calculate the VOC concentration, depending on the materials used in the model. This tool may be used as an extra certification for the indoor environment, especially when initiate new building, where materials may not yet have fully emitted.

An interactive collaboration between all imaginable building performance attributes ranging from simple VOC concentration calculation to comprehensive LCA should therefore be standardized to ensure the best possible compromise between the infinite possibilities.

5. CONCLUSION

Different applications have been investigated regarding thermal comfort, IAQ, and the compatibility with BIM. The study presents a list of 9 tools for simulating parameters related to thermal comfort and IAQ. Each tool is evaluated regarding the possibilities to collaborate with other tools, and thereby embrace the BIM methodology. Some tools are not yet prepared for interactive collaboration, and a data extraction is necessary for delivering the needed data as input in other tools.

This data extraction and file conversion is an action for further investigation. Besides, simple additions to a comprehensive energy analysis, will enable thermal comfort results, instead of just a temperature. Which is the true purpose of buildings.

Generally, the tools produce specific results, which cannot stand alone and must be compared with different simulations in other tools. As changing one parameter might improve the results in one view, but most likely compromises the results in other views. Therefore, an interactive collaboration between, not just the tools investigated in this research, but all parameters affecting the building from early conceptual phases, till the demolishing of the building, is necessary to establish the best compromise. This should be possible with the methodology of BIM.

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III

Building Information Modeling for Indoor Environmental Performance Analysis – Energy efficiency and Moisture comfort

Andreas Bøving

Abstract

BIM and sustainability are two well discussed topics in the building industry. They are both very important for making a high-performance building project. Indoor environmental performance has a lot of different areas from a high performing design team, that are using the IED methods, to how the information is exchanged from information model to performance calculation software. The software on the market has different properties from how to visualize to what building phase it should be used. Energy efficiency and moisture comfort are two important topics, that should be investigated when making performance calculations. There is still a lot of gaps in the industry when it comes to software, special with the collaboration with software that use Danish standards to calculate performance.

Key words

BIM, Sustainability, Early design phase, Energy efficiency, Moisture comfort, Software, Exchange formats

1. Introduction

With the increased awareness of energy consumption as well as the environmental impact of building operations, architects, designers, and planners are required to place more consideration on sustainability and energy performance of the building.

Building Information Modelling (BIM) and energy simulation tools are increasingly used for the analysis of energy efficiency of building and comfort of their occupants. This paper will be about how BIM and sustainability is related. There will also be focused on two chosen topics that originates from the specializing Indoor and Energy engineer. The chosen ones are energy efficiency and moisture comfort, which is two very different topics but very important for making a high-performing project.

Due to the decrease of hardware cost and the increase of computer speed and storage since 1970's, increasing numbers of computer building modelling tools are made available. With the development of BIM technology, complicated building modelling can be digitally constructed with precise geometry and accurate information to support the project construction, fabrication, analysis, and procurement activities. [1] Several studies in recent years show that tedious manual data input for building energy performance and consumption simulation diverts time and resources from productive simulation runs, also because of the fact that data defining a building, its heating, ventilation, and air conditioning (HVAC) and lighting systems and its expected pattern of use and operating schedules, is managed by different and non-interoperable software. [2] By using the part of BIM that is related to technology, it makes it possible for collecting all the information in one place and run performance simulation faster and with a knowledge that you are working with the relevant information.

In a building project is there different phases where the building develops, see Figure 1. BIM can be a crucially part in the phases when developing a building project. It is therefore important to have a knowledge about the different technologies that are on the marked, and in what phase they are most useful.

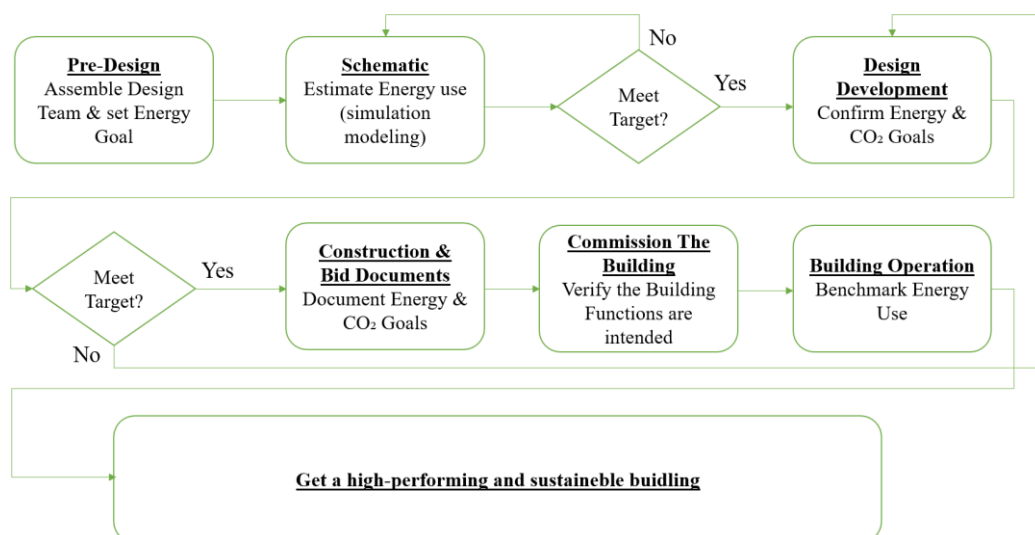


Figure 1. Incorporating energy targets, analysis and tracking during design and operation phases of the building, inspired from [3]

It is in the first three phases (early design phase) that the most important decisions should be made, not only because of the economy but also to make as many integrated passive solution, e.g. the orientation, as possible. The detail level is developing through the phases, so when choosing a BIM technology for making performance calculations should this be in mind. An example could be the Pre-design where there only are some conceptual masses, and the designing is in the macro level, there is non-analytical information to work with. Here would

it be smart to use some tool that quickly could set some default values in to see how the building is performing, like Green Building Studio.

The report is divided up in different sections where at first a literature study is made to gain knowledge and find the state of the art. It is covering the subject's sustainability, BIM, and indoor environmental performance. The Indoor environmental performance is directed the energy and indoor climate engineer, and it is chosen to investigate how the exchange formats are working, to get a better understanding on what certifies a software as a BIM software. The subsequent sections are about the chosen topics, energy efficiency and moisture comfort. It is investigated what software that are available to make the necessary calculations and what they can contribute with.

2. BIM and sustainability

BIM and sustainability is to subjects that goes hand in hand when it comes to make a high-performance project. [4] One of the unique benefits of BIM is the ability to use the building geometry from the model in other applications to speed some of the analyses that needs to occur for sustainability design principles. [5] Optimizing the integrated strategies and technologies for a high-performance, sustainable design requires a continual look at understanding how they work together to deliver the best potential. That is where BIM comes in, which gives you the ability to iterate and analyse faster than in a more traditional process. [5]

The combined future of BIM and sustainability can help us move faster and more elegantly to a restored world and a healthy planet. There is no future, no next, if we do not change the ways in which we work, live, and play. Without overstating the connection between BIM and sustainable design, a few things are inevitable. [5]

2.1 Sustainability

When the subject sustainability is discussed, is it often the impact on our planet that is highlighted but sustainability is so much more. A sustainability design is better than a green one because sustainability considers a greater array of impacts that just those that burden the natural environment. [5]

Sustainability has been a major issue in Architecture, Engineering, and Construction (AEC) industry since the energy crisis and arising concerns for the climate change. [1]

According to [5] there is four steps that can break down the process for a sustainable design with respect to the reducing of energy consumptions: 1. Understanding climate, 2. Reducing loads, 3. Using free energy, 4. Using efficient systems.

To accommodate the relative new interest in sustainability is there different originations in different countries, that has invented different certification methods for achieving a healthy and high performance space. There are over 15 different certification systems [6] some is used national and some international. Leadership in Energy and Environmental Design (LEED) is one of the most used one, it is developed in U.S and it is built around some of the most important areas when it comes to sustainability: Building Form, Energy, Pollution, and External cost to society [5]

In Denmark is it often the German made certification DGNB that is used, it has many of the same properties as LEED does.

2.2 BIM

Before BIM was invented many of the essential decisions that were made in the early stages of the design process, were taken out any valid and certain information. To resolve this some researcher and practitioners began to develop BIM, to support their information and presumptive calculation capability. [7]

There are some projects that still works by the "old way" where it is the traditional two-dimensional drawings where there are gaps of information between the different parties in the project team. These gaps with information, will exists all through the project phases.

In contrast, a BIM model includes all geometry, physical characteristics and data needed to describe the building. Then, all drawings, schedules, some simulations, and service required during the building life cycle can be extracted from the model.

In the AEC industry, there is a misconception by some that BIM is only a piece of software or tool. Although the software is a necessary part of this process, it is much more than an application. When we refer to BIM, we are discussing the methodology or process that BIM creates. [5]

This methodology is used to adapt information, allowing new methods of data exchange and communication amongst the stakeholders in a project. The goal of a BIM methodology is to allow an overall view of the building or project by including everything in a single-source model. [5]

A major objective is to develop an automated methodology that helps a designer do 3D conceptual design of a sustainable building and to analyse and simulate its energy use. [8]

When creating a BIM, model is it important to make sure that it is well executed, the BIM model will only be as accurate as the quality of information that goes into it. [5]

BIM allows multidisciplinary information to be superimposed within one model, this creates the opportunity for sustainability measures and performance analysis to be performed throughout the design process. [3]

BIM has the capability to help users assess different design alternatives and select vital energy strategies and systems at the conceptual design stage of proposed projects. Furthermore, by using BIM tools, designers can select the right type of materials early during the design stage and to make energy-related decisions that have significant impact on the whole building life cycle. [8]

BIM allows parametric design and building performance analysis. Nowadays BIM software integrates thermal, daylight, energy, and Computational Fluid Dynamic (CFD) performances simulation. [1]

Presently, BIM technologies have the option to provide users with an opportunity to explore different energy saving alternatives early in the design stage, thus avoiding the time-consuming process of re-entering all the building geometry and other supporting information necessary to complete the energy analysis. [8]

3. Indoor Environmental Performance

To have the highest impact on the energy use of a new building project, does the decisions must be made in the early design stage of a building. Many studies had concluded that the best opportunities for improving building indoor comfort performance occur in the early design or pre-construction stages. [1] For making these decisions can the use of an integrated energy design(IED) team be used. In fact, the potential for energy savings is significant if energy efficiency measures, combined with a better systems integration are, incorporated at the design stage. [3] [8] An important aspect of the IED method is to have all members of the team to sit down early in the process to contribute with their knowledge, this will give a more complete scope definition. The team include, the design team and all affected stakeholders. Success during the detailed design, construction, and start-up phases of a project is highly dependent on the level of effort expended during this scope definition phase. [3]

A fundamental tenet of true sustainability is integration of all building systems within themselves as well as with the external economic and environmental realities of the project. When the entire design team can actively share one another's work on the whole building, true integration becomes more real and compelling. Active sharing requires a method that allows free-flowing and constant communication. [5] This method that is required for achieving this communication could be solved by implementing BIM. During information exchanges between project participants, the level of detail of the information exchanged is critical for achieving sustainability goals. [9]

Use of an energy modelling, BIM, and intensive coordination among the design team members is imperative to achieving the designated energy consumption goals. [3]

When it comes to indoor environmental performance, are there a range of different measures that can reduce a building need: Building orientation, building massing, optimized glazing, optimized shading, optimized

lighting, passive solar, thermal mass, natural ventilation, and optimized mechanical systems. All these different measures are important to incorporate early in the early design phase, to make sure that the building will perform highest possible.

Interoperability is the ability of two or more systems or components to exchange information and to use the exchanged information. This is the crucial concepts in the BIM process. [2]

There are two exchanged formats that are mainly used in the industry for using the interoperability between programs and applications:

IFC: The industrial Foundation Classes is an industry-developed standard for the design and full life cycle of buildings, and is usually used by model-based applications.

gbXML: The Green Building XML is a scheme developed to transfer information needed for preliminary energy analysis of building envelopes, components and location, thermal zones, mechanical equipment simulation and material thickness.

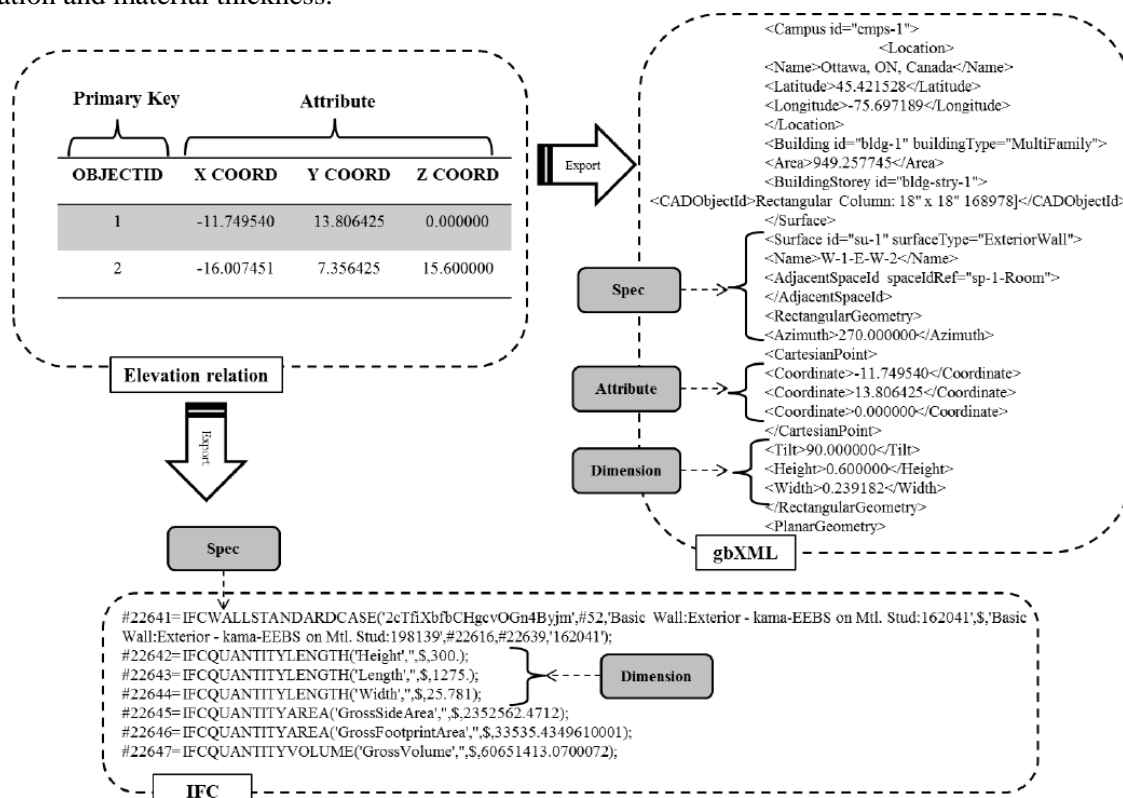


Figure 2. Example of wall information exchanged through gbXML and IFC file formats [8]

Figure 2 shows that gbXML and IFC do not contain the same information's about the building. It shows that the IFC file contains geometric information such as shapes, areas and volumes but is not populated with other critical information such as location, construction assignments and units. The gbXML file, like IFC, contains geometric and construction assignments. The gbXML file does also include other information such as building type, and building service.

Unfortunately, despite the use of these exchange formats, importing geometry data into energy simulation software has limitations and usually includes either a process of iteratively changing the architectural model or manually checking and fixing the partially converted geometry. [2] An example could be a triangle window in Revit would be handle, by the exchange formats, as a squared window.

4. Energy efficiency and moisture comfort

Energy efficiency and moisture comfort are two topics that are independent of each other. The Energy efficiency relates to the performance of the building where the moisture is more related to the indoor climate comfort.

Energy and performance analysis are typically performed after the architectural design and construction documents have produced, if at all. This lack of integration into the design process leads to an inefficient process of retroactively modifying the design to achieve a set of performance criteria. [3]

The Energy efficiency and moisture comfort analyses is both to impotent analysis that should be made in the design phase to get a high-performing building.

4.1 Moisture comfort

Humidity of indoor air is an important factor influencing the air quality and energy consumption of buildings as well as durability of building components. Indoor humidity depends on several factors, such as moisture sources, air change, sorption in materials and possible condensation.

Moisture data is something that goes hand and hand with temperature data because it is these two together that determine overall thermal comfort. To capture the relationship between temperature and moisture, you need to gather monthly average dew point temperatures. Dew point temperatures are available through the same sources that you get the temperature data. High average dew point temperatures suggest potential for human discomfort if they are close to the average temperature. When dew point and temperature are close in value, this is commonly expressed as a high relative humidity. High temperatures tell our body to cool by sweating, and high relative humidity inhibits evaporation of sweat. These combined conditions of high temperature and high dew point create human discomfort. [5]

4.2 Energy efficiency

It is commonly known that the energy consumption of buildings is quite high; therefore, owners, architects and engineers should be more concerned about the sustainability and energy performance of proposed building projects.

Energy efficiency has different aspects, it relates to sustainability and to annual operating cost. This to subjects are often misunderstood and thought not to be linked, but often when a building is designed out from sustainable design concepts is the annual cost lower than normal.

According to [5], as you increase the energy efficiency of the design by adding some of the lesser individual measures, not only does the annual operating cost begin to drop but so does the first cost of the project. The reason for the drop-in costs is simple: these strategies are dependent on each other.

5. BIM for energy efficiency and moisture analysis

There are a range of different software on the market to perform performance calculations for analysing energy efficiency and moisture comfort. The different software has a range of pros and cons. Table 1 shows some of the software on the market, and what they can offer.

Table 1. Overview over software for performance calculation

Software	BIM ¹	Plug-in ²	Cost free ³	Dynamic ⁴ Calculation	Result ⁵ Visualization	Result ⁶ Comparable	Project ⁷ Phase
Vabi Apps	X	X	-	-	X	X	A,B
Sefaria Architecture	X	X	-	-	X	X	A,B
Green Building Studio	X	X	X	X	X	X	A,B
IES <VS>	X	X	-	X	X	X	A,B
Insight 360	X	X	X	X	X	X	A,B
Built – in Revit	X	X	X	X	-	-	B
IDA-ICE	-	-	-	X	-	-	B,C
Bsim	-	-	-	X	-	-	B,C
TRYNYSYS	-	-	-	X	-	-	B,C
IceBear	-	-	X	X	-	-	B,C
IdBuild	-	-	X	X	X	X	B,C
Be15	-	-	-	-	-	-	B,C

¹All the software that are marked in the column for BIM can collaborate with Revit. In the time of studying engineering has there been presented a range of different programs that can calculate energy use and environmental performance. The problem with almost every program is that it does not support the technologies of BIM. Some of them can load a geometric file, but they cannot load the exchanges files IFC or gbXML.

²The software that have developed a plug-in to Revit is often also known as a BIM software. Some of them has also a cloud based application, e.g. Green Building Studio (GBS) and Insight 360.

³Is showing whether the software is free or has a cost. This is often an important factor for whether the software is attractive.

⁴The definition for dynamic is that it uses a hourly calculation to execute the performances calculation, which include a weather file.

⁵The Result visualization is based on how the software is displaying the result. Some of the software is minded an architect, and architect works often best with some visualizations for displaying the result and consequence of the choices made.

⁶The Result comparable is a very useful tool to see the consequence of the changes to the model and is making it easier to make the decisions.

⁷As shown in Figure 1 is there different phases in a building project. **A** is indicating that the software is useful in the conceptual design where it sometimes only is a mass that are designed. **B** is indicating that it works well with zones and the whole building. Here is an analytical model necessary for performing performance calculations. **C** is indicating that the software can make very accurate calculations, and is using the Danish standards, for calculation the energy use and the indoor comfort.

5.1 Energy efficiency

One of the chosen topics was energy efficiency, there is therefore made a table that displays how the software, introduces in Table 1, can be used for calculation topics in relationship with that.

Table 2. Overview over software for energy efficiency

Software	Total load ¹	Component load ²	Space load ³
Vabi Apps	X	-	-
Sefaria Architecture	X	X	X
Green Building Studio	X	X	X
IES <VS>	X	X	-
Insight 360	X	X	X
Built – in Revit	X	X	X
IDA-ICE	-	-	X
Bsim	-	-	X
TRYNSYS	X	X	X
IceBear	-	-	X
IdBuild	-	-	X
Be15	X	-	-

¹Total load is calculation the whole buildings energy use in watts. This is very useful to see how the building will perform.

²The definition with component load, is that the software can calculate the energy loss through a construction material, like walls. This is a great tool for making energy efficiencies because then it is known what component that has the largest influence on the energy loss.

³Space load can calculate how a space/room is performing with regards to the energy loss. With this is it possible to locate a space that has a large influence on the total energy loss, and then optimize on that space.

Much of the software that are designed for the early design phase can calculate the total energy use, which is very useful for making some essential energy efficiency choices early in the building project.

5.2 Moisture comfort

The other chosen topics was moisture comfort, there is therefore made a table that displays how the software, introduces in Table 1 can be used for calculation topics in relationship with that.

Table 3 Overview over software for moisture comfort.

Software	Relative humidity ¹	Bulb temperaute ²	Finite element ³
Vabi Apps	-	-	-
Sefaria Architecture	-	-	-
Green Building Studio	X	X	-
IES <VS>	X	X	-
Insight 360	X	-	-
Built – in Revit	X	X	-
IDA-ICE	X	X	X
Bsim	X	X	X
TRYNSYS	X	X	X
IceBear	X	X	-
IdBuild	X	X	-
Be15	-	-	-

¹Relative humidity is very useful for determine the indoor comfort. Some software calculates it on the whole building like the built-in, but Insight 360 calculates it for the different zones.

²The bulb temperature is like the relative humidity a way for calculate how the indoor comfort is with respect to moisture.

³The definition for finite element is that it is using a numerical method for calculating. In this context is it the moisture transport through the construction that it should calculate.

Where before much of the software was for the early design phase when it comes to energy efficiency. It is more some of the more the accurate calculating software that is used for the precise moisture comfort but for

this the model must have a high detail level. But the software for the early design phase is very useful for gathering an idea of how the comfort is in the building before going further in the process.

6. Analysis

To show some of the opportunities in the software are there made some performance calculations on a small model in Revit. There are used the build-in components and Insight 360.

6.1 Built-in Component

To calculate how a building is performing you have to implement zones in the building. When that is done, you can choose the Heating a Cooling Loads in Revit. Here there is the opportunity for implement some parameter values or use the default ones. The calculation give a schematic overview over the whole building and the zones performance.

Based on the two chosen topics is there displayed some of the results that is possible to get in with this method. See the whole table in Appendix 1.

Energy efficiency: Under the Building Summary it is possible to see how the whole building is performing. It is then possible to compare different projects on how much energy they use, and then find what changes that gives the best result.

Moisture comfort: The moisture calculation is based on the zones. There is a section in the table called Zone Summary - Default. Here can the Relative Humidity and the Dry and Wet bulb be read.

The Built-in component is not a BIM software but it gives the opportunities for making fast performance calculations.

6.2 Insight 360

As described earlier Insight 360 is an application from Autodesk that can be implemented into Revit. It is based in the EnergyPlus engine, which provides a fast and precise calculation. Before using it should the buildings rooms be assigned. When that is done, you chose the Generate Insight, and the model will then be analysed on a server, and you will get a message on email when it is done. In the application platform is it possible to compare models or chose to perform some improvements on one model. The platform is more useful for the energy efficiency analysis then the moisture analysis. The moisture analyses should be performed using the other application Insight offers. This is the option to make a heating and cooling calculation using the EnergyPlus engine.

Energy efficiency: As described the platform gives a range of opportunities for making energy efficiencies to the model.

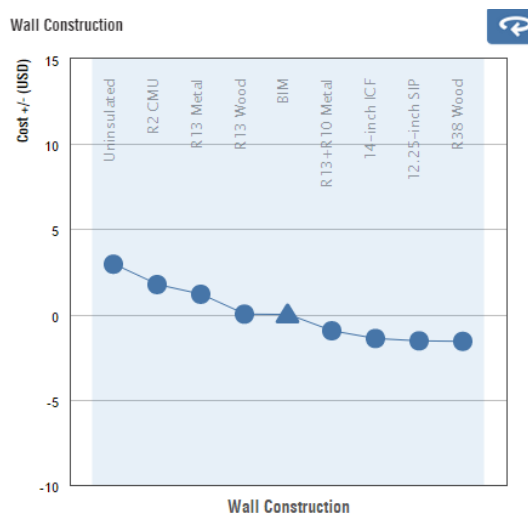


Figure 3. Insight 360 showing the opportunity's for making some energy efficiency's by changing the wall construction

Figure 3 shows how it could be possible to make some improvement to the wall construction. This is extremely useful when making energy efficiency's. It is speeding up the process and by that making it more attractive for the user. This was only an example, there is a range of possibilities to make these improvements.

Moisture: The application that is accompanying Insight 360 that can calculate heating and cooling with the EnergyPlus engine, is very useful for getting a schematic overview over how the model is performing. It separates itself from the built-in component by the opportunity for analyse the rooms separately.

Inputs	
Area (SF)	501.37
Volume (CF)	5100.58
Cooling Setpoint (°F)	75.02
Heating Setpoint (°F)	64.93
Relative Humidity (%)	56.19
Calculated Results	
Peak Cooling Total Load (Btu/h)	27203.24
Peak Cooling Month and Hour	7/21 09:00:00
Peak Cooling Sensible Load (Btu/h)	26880.09
Peak Cooling Latent Load (Btu/h)	323.15
Peak Heating Load (Btu/h)	-9690.10
Checksums	
Cooling Load Density (Btu/(h·ft²))	54.26
Heating Load Density (Btu/(h·ft²))	-19.33

Figure 4. The table for how level 1 in the model is performing

Figure 4 shows some geometric measurements and temperature set points. The interesting in respect to the moisture calculations is the Relative humidity that is accessible. With this is it possible to calculate how the occupants will feel in the room, and thus make a great indoor climate.

Insight 360 is an extremely strong software as a BIM tool. It gives the opportunity for quick calculations a smart looking visualization that gives a good overview of the opportunities for building improvements.

7. Discussion

BIM is an interesting and popular subject, with a lot of literature accessible on the internet. With all this literature it is necessary that you are aware of the quality of it, to make sure it is relevant.

Because of the rapidly development of BIM, is the release date of the paper or book extremely relevant. Many of the things for just only a few years ago, is now old news. The software is constantly developing to be more flexible and more user friendly.

In the analyse of what software that are accessible for performing performance analyses, and simultaneous be linked to an information model like a Revit project, are there some topics that are not experienced but read from websites like [10].

As the report shows is there a range of different BIM software that can be used in the early design phase. In the later phases where there is a higher detail level is it not the same picture. All the software, that are focused on in this report, that can perform precise calculations cannot be used as a link to the Revit model. This is a problem because many of the Danish engineers is using software like Bsim and Be15, and with the missing link between the information model and the software is it not possible to transport the information between them. To implement BIM sufficiently is it necessary to develop a converter that can transform the information from the model so the software can read it. But because of fast development in this area will it properly not take long time before that is possible.

8. Conclusion

BIM has a range of benefits some of them is that it can speed up some of the analyses that are necessary for a sustainable project.

Based on the research can it be concluded that much of the software that is related to BIM, and can make performance calculations, is developed for the early design phase. The early design phase is the phase with the highest influence on how the building will perform and the sustainability of the project.

Energy efficiencies is an extremely important topic for getting a sustainable project. Much of the software that are linked with BIM can make total energy loss for a building, which is a strong property in the early design phase, where it is also here it has the greatest impact on the project.

Moisture comfort can be used in different phases of the building project, and there is a range of different software that can calculate different aspects of it. Much of the software that is used in the early design phase is calculating the relative humidity which is good for estimating indoor comfort. Where the finite element software is useful for moisture transport through construction and it is therefore more useful in the later phases. These software is not linked to BIM which is not making them as attractive as the ones that are.

The BIM methodology is in a fast development, with constant new software and features. Because of the fast development is it necessary to constant be aware of the state of art.

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Appendix 1

Project Summary

Location and Weather	
Project	Project Name
Address	
Calculation Time	12. marts 2017 16:45
Report Type	Standard
Latitude	56.18°
Longitude	10.19°
Summer Dry Bulb	26 °C
Summer Wet Bulb	21 °C
Winter Dry Bulb	-5 °C
Mean Daily Range	12 °C

Building Summary

Inputs	
Building Type	Dormitory
Area (m ²)	121
Volume (m ³)	465.65
Calculated Results	
Peak Cooling Total Load (W)	21,786
Peak Cooling Month and Hour	July 08:00
Peak Cooling Sensible Load (W)	21,502
Peak Cooling Latent Load (W)	283
Maximum Cooling Capacity (W)	21,786
Peak Cooling Airflow (L/s)	1,139.1
Peak Heating Load (W)	9,256
Peak Heating Airflow (L/s)	444.5
Checksums	
Cooling Load Density (W/m ²)	180.32
Cooling Flow Density (L/(s·m ²))	9.43
Cooling Flow / Load (L/(s·kW))	52.29
Cooling Area / Load (m ² /kW)	5.55
Heating Load Density (W/m ²)	76.61
Heating Flow Density (L/(s·m ²))	3.68

Zone Summary - Default

Inputs	
Area (m ²)	121
Volume (m ³)	465.65
Cooling Setpoint	23 °C
Heating Setpoint	21 °C
Supply Air Temperature	12 °C
Number of People	13
Infiltration (L/s)	0.0
Air Volume Calculation Type	VAV - Single Duct
Relative Humidity	44.00% (Calculated)
Psychrometrics	
Psychrometric Message	None
Cooling Coil Entering Dry-Bulb Temperature	28 °C
Cooling Coil Entering Wet-Bulb Temperature	19 °C
Cooling Coil Leaving Dry-Bulb Temperature	12 °C
Cooling Coil Leaving Wet-Bulb Temperature	13 °C
Mixed Air Dry-Bulb Temperature	28 °C
Calculated Results	
Peak Cooling Load (W)	21,786
Peak Cooling Month and Hour	July 08:00
Peak Cooling Sensible Load (W)	21,502
Peak Cooling Latent Load (W)	283
Peak Cooling Airflow (L/s)	1,139.1
Peak Heating Load (W)	9,256
Peak Heating Airflow (L/s)	444.5
Peak Ventilation Airflow (L/s)	0.0
Checksums	
Cooling Load Density (W/m ²)	180.32
Cooling Flow Density (L/(s·m ²))	9.43
Cooling Flow / Load (L/(s·kW))	52.29
Cooling Area / Load (m ² /kW)	5.55
Heating Load Density (W/m ²)	76.61
Heating Flow Density (L/(s·m ²))	3.68
Ventilation Density (L/(s·m ²))	0.00
Ventilation / Person (L/s)	0.0

Components	Cooling		Heating	
	Loads (W)	Percentage of Total	Loads (W)	Percentage of Total
Wall	-78	-0.36%	1,405	15.18%
Window	18,432	84.61%	6,724	72.65%
Door	7	0.03%	190	2.05%
Roof	-20	-0.09%	937	10.13%
Skylight	0	0.00%	0	0.00%
Partition	0	0.00%	0	0.00%
Infiltration	0	0.00%	0	0.00%
Ventilation	0	0.00%	0	0.00%
Lighting	918	4.22%		
Power	1,377	6.32%		
People	693	3.18%		
Plenum	0	0.00%		
Fan Heat	455	2.09%		
Reheat	0	0.00%		
Total	21,786	100%	9,256	100%

Default Spaces

Space Name	Area (m ²)	Volume (m ³)	Peak Cooling Load (W)	Cooling Airflow (L/s)	Peak Heating Load (W)	Heating Airflow (L/s)
1 Space	60	244.14	10,679	570.2	4,246	203.9

Space Summary - 1 Space

Inputs	
Area (m ²)	60
Volume (m ³)	244.14
Wall Area (m ²)	131
Roof Area (m ²)	0
Door Area (m ²)	2
Partition Area (m ²)	0
Window Area (m ²)	41
Skylight Area (m ²)	0
Lighting Load (W)	650
Power Load (W)	975
Number of People	7
Sensible Heat Gain / Person (W)	73
Latent Heat Gain / Person (W)	59
Infiltration Airflow (L/s)	0.0
Space Type	Dormitory (inherited from building type)
Calculated Results	
Peak Cooling Load (W)	10,679
Peak Cooling Month and Hour	July 08:00
Peak Cooling Sensible Load (W)	10,537
Peak Cooling Latent Load (W)	142
Peak Cooling Airflow (L/s)	570.2
Peak Heating Load (W)	4,246
Peak Heating Airflow (L/s)	203.9

Components	Cooling		Heating	
	Loads (W)	Percentage of Total	Loads (W)	Percentage of Total
Wall	-39	-0.37%	695	16.36%
Window	9,216	86.30%	3,362	79.18%
Door	7	0.07%	190	4.46%
Roof	0	0.00%	0	0.00%
Skylight	0	0.00%	0	0.00%
Partition	0	0.00%	0	0.00%
Infiltration	0	0.00%	0	0.00%
Lighting	459	4.30%		
Power	689	6.45%		
People	347	3.25%		
Plenum	0	0.00%		
Total	10,679	100%	4,246	100%

Space Summary - 2 Space

Inputs	
Area (m ²)	60
Volume (m ³)	221.51
Wall Area (m ²)	131
Roof Area (m ²)	61
Door Area (m ²)	0
Partition Area (m ²)	0
Window Area (m ²)	41
Skylight Area (m ²)	0
Lighting Load (W)	650
Power Load (W)	975
Number of People	7
Sensible Heat Gain / Person (W)	73
Latent Heat Gain / Person (W)	59
Infiltration Airflow (L/s)	0.0
Space Type	Dormitory (inherited from building type)
Calculated Results	
Peak Cooling Load (W)	10,652
Peak Cooling Month and Hour	July 08:00
Peak Cooling Sensible Load (W)	10,511
Peak Cooling Latent Load (W)	142
Peak Cooling Airflow (L/s)	568.8
Peak Heating Load (W)	5,009
Peak Heating Airflow (L/s)	240.5

Components	Cooling		Heating	
	Loads (W)	Percentage of Total	Loads (W)	Percentage of Total
Wall	-39	-0.36%	710	14.17%
Window	9,216	86.52%	3,362	67.12%
Door	0	0.00%	0	0.00%
Roof	-20	-0.19%	937	18.71%
Skylight	0	0.00%	0	0.00%
Partition	0	0.00%	0	0.00%
Infiltration	0	0.00%	0	0.00%
Lighting	459	4.31%		
Power	689	6.47%		
People	347	3.25%		
Plenum	0	0.00%		
Total	10,652	100%	5,009	100%

IV

Building Information Modeling for Indoor Environmental Performance Analysis – Acoustic Comfort and Indoor Air Quality (IAQ)

Maria Leonhard Christensen

Abstract

Sustainability and attention to low energy consumption buildings are increasing. BIM is a great way to obtain these high-performance buildings. With the possibility to make performance analyses in the design phases, the final design is not only based on aesthetic but also on its performance. In this report the possibilities to make acoustical and indoor air quality analysis in a BIM connection was investigated. Research showed, that there is a lack of attention to both areas when working with major BIM software. Still there are simulation tools available, but the ability to link other than geometrical data is missing. Software like Pachyderm and CATT for acoustic analysis has potential but is missing the BIM link. Regarding IAQ, software like iDbuild shows a calculation procedure which can be implemented as an explicit plugin to a 3D BIM model. A development in linking these simulation tools to a BIM environment is necessary for acoustic comfort and IAQ to become a part of the full environmental analysis.

Key words

BIM, Sustainability, Acoustic Comfort, Indoor Air Quality (IAQ)

1. Introduction

Sustainability has become a common used expression during the last decades. Still, it can be hard to make an accurate definition as the term is used *laissez faire*. The attention to the area is necessary as science shows the human impact on the earth as well as decreasing amount of resources. By integrating the sustainability aspect in procedures, it can help lowering this negative impact. As [1] describes it:

“Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs.”

The future is not affected by the choices of the present; instead there is a balance. The balance is between three areas; people, planet and prosperity [1]. With a holistic approach including these three areas, a sustainable solution can be created. These areas should also be considered in the building industry. A complete sustainable building should care for the health of the occupants, minimize the impact on the planet and still be a gain for the investor. The gain can be savings in the traditionally way due to lower energy consumption, but it can also be due to a more productive staff, because of the well indoor environment, which has proven to influence the effectiveness [2]. Often the sustainable focus is mainly on the construction and operational part of the building phase, whereas a sustainable solution suggests an evaluation of the total lifespan of a building, including the construction part, operational part as well as the demolition of the building. The three sustainable areas are further described in the following section with the building industry in mind.



Figure 1: The three areas which creates a sustainable solution. There should be a balance between these areas.

People: The main purpose of making a building is to create an internal space protecting the people. But the building itself can create a bad and unhealthy environment. It is therefore essential that the building is a healthy and calmly environment which do not affect the occupants in any negative way.

Planet: The use of resources is a constant issue. In EU, the energy consumption from houses is 40 % of the total energy amount being used. A sustainable building should minimize the energy consumption in the operational stage, but also by considering the use of materials etc.

Prosperity: This area has earlier, and are still, an important part of a sustainable solution. Not many corporations, investors and firms are interested in a sustainable building, if there are no positive effect on the economy. A sustainable building design often has an economic benefit. As earlier described the benefit can be directly from a lower energy consumption but also indirectly by the improvement of the productivity of the employees.

Integrated Energy Design (IED)

With the technical development, it is more likely to explore design concepts and predict the performances with software. The computational simulations can be very helpful when designing a building who should meet the earlier described sustainable criteria. With these possibilities, the designers should not only take aesthetic and design into account but also consider the consequences of the design decisions compared to stability, indoor climate, energy consumption etc. This will cause a closer collaboration between architects and engineers which also is called the IED. This new approach will involve a process with collaboration between different work areas as well as information exchange. The use of BIM can become a major gain as a part of this process.

The thought of mixing design and performance is not new. Before the inventions of HVAC systems and artificial lighting, the architect had to have elements like ventilation and light in mind when creating the building. The development of mechanical ventilation systems and electrical light gave the architect new possibilities in the creation of the building as he was no longer constrained. [3]. Instead the engineer solved the subsequent problems. The traditional sequential design process does not incorporate with these issues and leaves a non-unified building concept. Whereas the more conventional design process is divided into the different areas of interest, the Integrated Design Process suggest an iterative approach where a design team of architects, engineers and other relevant experts collaborate to find a united design where consideration about aesthetic and performance is the base of the design decision.

Building Information Modeling in the Design Process

The development of BIM supports the thought of a close collaboration in a design team with different disciplines. The definition of BIM is wide; one suggestion describes BIM as *a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a facility in virtual space.* [4]

The collaboration is based in a common digital 3D model, which can be develop from every part of the design team and leave the rest updated with the changes. This structure streamlines the flow when exchanging information because of the common platform, see Figure 2. This organization strategy also minimizes the risk of losing information when collaborating.

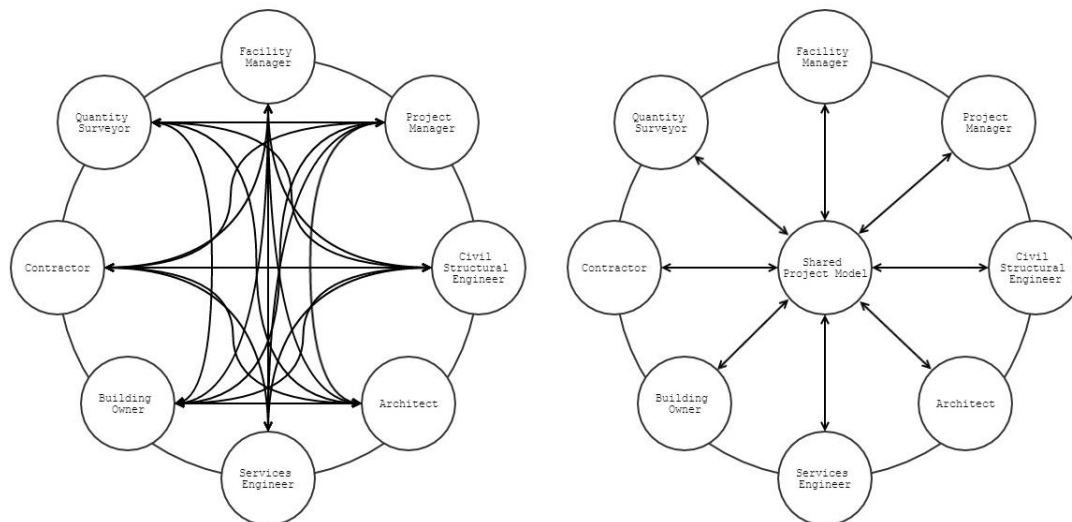


Figure 2: The information exchange with the traditional way and with a shared project model.

A BIM model is essential when deciding on a building design. Even though the early stages of the architectural design process mainly consist of sketches and drawings, the designer decides on substantial factors for the building performance such as orientation, building shape, building envelope etc. These decisions are based on inadequate information, that a simulation of a building model could provide [5]. Even though the level of detail is low, it is still possible to make simple simulations to provide more information to rely the decision on.

Design phases and level of detail (LOD)

The IED is a part of the different design phases which has an individual LOD. This level will increase until the full, detailed project can be handed to the contractor. Even though a building project is a unique process, the project often follows the same design phases. A typical design process of a building is illustrated in Figure 3.

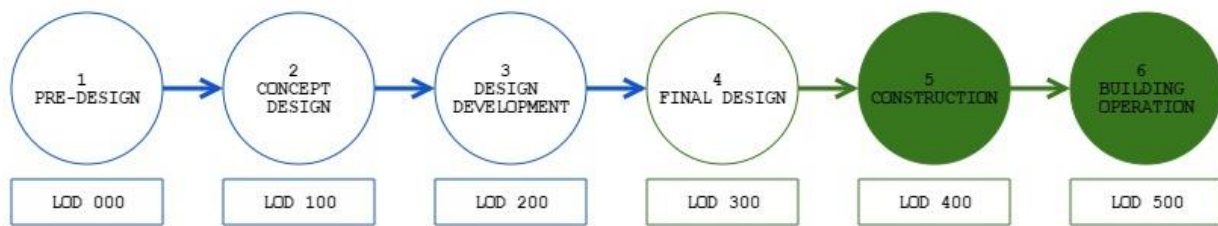


Figure 3: Typical Design Process of Buildings and the level of detail in each phase.

Traditionally, the decisions in the beginning of a project are based on a low LOD. With the IED process, early simulations will help the decision maker in this process by calculating the performance of the concept design. The first simulations are based on assumptions because of the low LOD. As the process continues and the LOD increases, the simulations become more accurate. The phases and their LOD are described below. The section is based on [6]. Phase 4 and 5 are ignored because of the lack of relevance to this report.

Pre-Design (LOD 000)

First, requirements of the project, existing condition and other important information should be identified. A site analysis including sun and wind patterns can result in a design adapting or using these conditions as an advantage. The LOD is 000 because no digital model exists.

Concept Design (LOD 100)

In this phase a creative, experimental and iterative process is running in order to create a design for the building. A simplified BIM model is developed but the LOD is low because the model only contains of geometry and spatial relations. The model should be investigated based on the initial work in the Pre-Design Phase to determine how the building design performs with light, shadows and wind. Orientation of the building and fenestration should be considered.

Design Development (LOD 200)

The design is being further detailed according to material properties and thickness, mechanical and structural systems. The focus is on detailing. The BIM model contains a LOD 200-300 as materials are chosen. A MEP model with routings for plumbing, heating/cooling and ventilation systems has a LOD 200. With the material properties and thickness, the energy analysis of the model becomes more reliable. Also, interior daylight analysis to determine amount of artificial lighting is possible and the efficiency of the mechanical system can be investigated with a cooling/heating load simulation.

Final Design (LOD 300)

The specifications of the buildings should now be finished. The model has a LOD 300 with the final materials and building elements. It is possible to make a detailed energy analysis of the whole building to document expected performance. Also, final expected costs can be determined.

A BIM model has a central place during all the design phases and it is possible to continually making performance simulations and therefore optimize on the building design. There are many environmental simulations available, but in this report the focus is on acoustic comfort and IAQ. These will be investigated in order to be updated on state of the art knowledge on these topics in connection with BIM.

2. Indoor Environmental Performance

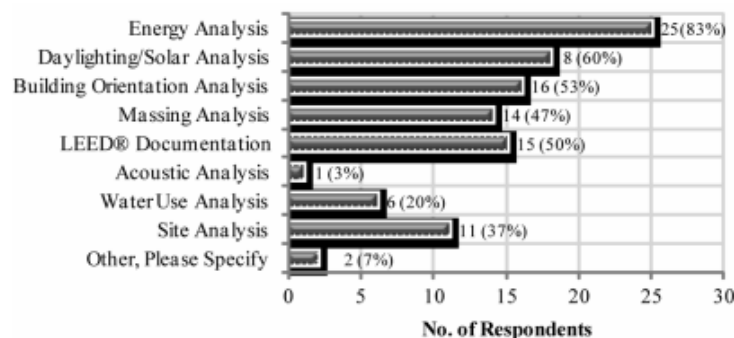
As earlier described a BIM model can provide several indoor environmental simulations and predict how the building will perform. As the BIM industry is developing, so is the number of simulation software, able to link to a 3D BIM model. In relation to sustainability, there are three authoring tools according to [7]. These tools are Autodesk Revit, Graphisoft Constructor and Bentley Architecture. Also, IES is a major company in this area and provide a similar tool. These four companies provide a great variety of software which can simulate and analyze 3D models within different areas. Some of these tools are:

- Autodesk Green Building Studio

- Graphisoft EcoDesigner
- IES Solutions Virtual Environment VE-Pro
- Bentley AECOsum Building Designer

The software provides different environmental simulations, which will be evaluated later in accordance to their performance in the chosen areas. The software is similar in their focus of BIM and how they can collaborate and interact with other programs.

Salman Azhar and Justin Brown determined the current state and benefits of BIM-based sustainability analyses [8]. Even though the data reflects the state of 2009, the survey showed a time and cost saving when using BIM-based sustainability analysis. In the survey, they also asked what kind of performance analysis the different companies made, see Graph 1.



Graph 1: Types of BIM-based performance analyses used by companies.

The graph shows that both acoustic comfort and IAQ are not preferable for analysis. The following sections provide a better insight in the importance of awareness of these areas and the tools available to make performance analysis.

2.1 Acoustic Comfort & IAQ

Acoustic

Acoustic is a very important area as it surrounds us at all time and will affect both our well-being and behavior. The awareness of the acoustical behavior in a building has increased through the last decades, but daylight conditions and energy consumption are still the main focus when working with indoor environment and energy. Acoustic is very important to considerate when designing the form and the material use of the building. If these considerations are not incorporated in the design of the building, it can cause problems and be difficult to solve later. Because acoustic is very depended on the building form as well as the materials, the lack of attention will end in a non-elegant, add-on solution instead of a united one.

Acoustic can be described with many different parameters. General parameters like reverberation time, early decay time and center time can be used, but also other parameters like clarity or deutlichkeit can be used for a more specific investigation music or speech [9]. The reverberation time can be calculated with a few inputs, where the other parameters need a simulation. This must be considered when choosing parameters. According to [6] the LOD in the design phase includes the finishes of interior walls as well as the geometry of the building. It is therefore possible to both calculate the reverberation time as well as make acoustical simulations.

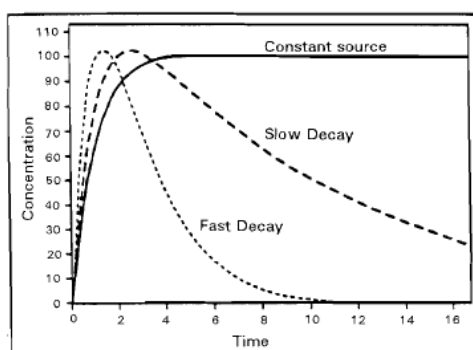
The Danish Traffic and Construction Board has released a set of guidelines, which The Danish Building Regulation refers to in the building regulations. These guidelines give different restrictions of noise and acoustic for different building types. For acoustic performance, only the reverberation time is used as a parameter. Therefore, this is essential to investigate this in order to accommodate the regulations.

2.2 IAQ

As well as acoustic comfort, IAQ has a major effect on the occupants of the building. Uncomfortable occupants can have a negative effect on their productivity and lack of attention of IAQ will therefore not only effect the health and wellbeing of the occupants but also the economy of the client. Even though the consequences are big, IAQ are often, like acoustic, being downsized compared to other environmental areas.

IAQ is a subjective topic as people interpret a room differently. It can therefore include multiple parameters. In this report IAQ involves two parameters; CO₂-concentration and Volatile Organic Compounds (VOC). CO₂ is a commonly indicator of the IAQ and ventilation system are often activated when high levels of CO₂ occur as well as high temperatures. According to the Danish Building Regulation there is a requirement of the CO₂-concentration not exceeding 0,1 % in non-residential buildings. IAQ can therefore not be ignored as the regulations must be accommodated.

VOC emissions from materials and furnishings are very important to quantify because it is a major part of the indoor pollutant [10]. Some materials will have a constant emission of VOC where others will decay the emission due to time, see Graph 2. When a building is finished, it is often necessary to wait an amount of time for the building to emission some of this VOC pollutant. The VOC emission should therefore be in focus when choosing materials.



Graph 2: The concentration of VOC emissions in the air depending on time of different types of sources.

There are many elements influencing IAC, including building materials, outdoor environment, building content, occupants and their activities as well as the operation and maintenance of the building and the HVAC system [11]. If IAQ is not discussed in the early design phase, these elements are not being considered. Many aspects should be considered when evaluating IAQ in the building process. Some of these aspects are:

- Site Planning and design
- Overall architectural design
- Ventilation and climate control
- Materials selection and specification
- Construction process and initial occupancy

Some of these aspects are not possible to consider in the design phase of the building. Because IAQ also depends on the perception from the occupants, it is necessary to follow up on this when the building is ready to use. But aspects like site planning, architectural design and materials selection can be considered beforehand in order to create a good base for a good IAQ.

3. BIM for Acoustic Comfort and IAQ analyses

Software

For the investigation of BIM tools in relation to acoustic comfort and IAQ a lot of different software has been investigated. Table 2 shows the most interesting software, their interoperability, input needed, output and their pros and cons. Some of them are further discussed in the following sections.

Table 2: Investigation of relevant software in accordance to acoustic comfort and IAQ simulations.

Software	Inter operability	Simulations tools		Input	Output	Pros	Cons
		Acoustic	IAQ				
IES	- Autodesk, REVIT - gbXML	-	- (Apache Loads)	-3D model (ModelIT) - Weather - Solar shading - Construction and materials - Thermal templates - HVAC systems	-Sizing ventilation systems based on IAQ requirements -Heating/Cooling loads	Broad variety of outputs	Not able to do a separate IAQ simulation.
Rhino ceros	- Graphisoft - (REVIT)	- - Pachyderm - Bizz	-	-Geometrical model -Materials	-Reverberation Time -Early Decay Time -Center Time -Clarity -Definition -Strength/Loudness	Many parameters can be simulated	Output in file format, no visualization of results
iDbuild	-	-	- iDbuild	-Number of people -Activity level -Clothing level	-Indoor Air Quality Class	Quick simulations	Only rectangular rooms with windows on one wall.
IAQX	-	-	-IAQX	-Number and volume of air zones -Number of Sink Materials -Sources, including source model, (e.g. source area, initial emission factor, decay constant)	-VOC	Quick calculations	No interoperability to 3D models
TUCI™ v2	-	-CAITP- Acoustic™ v9.1	-	-Geometrical model -Absorption coefficients	-Reverberation Time -Early Decay Time -Center Time -Clarity -Definition -Strength/Loudness Etc.	2D representation of output.	Only geometrical information

Acoustic

As a part of the technical development, a lot of acoustic prediction software have been developed and the computational modelling and simulation of rooms streamlines the process. It is possible to predict the acoustical performance of the building beforehand and in a much faster way than before, where physical models were necessary. Software like Odeon, CATT, EASE, Ramsete, SoundPlan, VNoise and SEAM 3D are some application which can perform these analyses. The advantage of the software is, that it is possible to import geometry from 3D CAD or SketchUp instead of creating a model in the software. E.g. It is therefore possible to make a 3D model in Revit and import this into Odeon. Unfortunately, it is only possible to import geometrical information and acoustic properties of the surfaces must be manually added afterwards. This is a barrier when connecting with a BIM model. To collaborate with a BIM model, the applications are limited because it is only the geometrical information which is imported and no acoustic data [12]. Also, the 3D model is also only imported and not continually updated when making geometrical changes. This link between the 3D model and the simulation tools as well as the incorporating the acoustic properties in the 3D model would be the next step to develop an acoustical simulation tool linked to BIM models.

Autodesk and acoustic analysis

As mentioned earlier, Autodesk, Graphisoft and Bentley are the biggest tools when making environmental simulations with digital models. Ecotect, an environmental simulation tool from Autodesk, claimed it could provide a variety of indoor climate and energy analysis, including acoustical simulation and could accommodate directly to BIM. Unfortunately, it lacked on the performance on this area [13]. The cause was primarily the file format. Whereas Ecotect imported gbXML files, these did not contain acoustic information and it had to be announced manually. Afterwards Ecotect has been integrated into Revit and is a part of the simulation system. Unfortunately, acoustical simulation has been discharged in the process.

Rhino and acoustic analysis

Rhinoceros can also provide 3D modelling. It has many plug-ins which can make multiple simulations in order to predict the buildings performance. One of these plug-ins, called Pachyderm, makes acoustical simulations. With this plug-in, a source and receiver can be placed in the 3D model and simulate both reflected and diffuse sound from the source to the receiver. Pachyderm provides a variety of parameters, including Reverberation Time, Early Decay Time, Center Time, Definition, Strength/Loudness and Clarity. 3D models in Rhinoceros can be linked to Graphisoft. Unfortunately, it is not possible to visualize the distribution of the sound with Pachyderm. Another plugin called Buzz can do the visualization in Grasshopper and Rhino. A simulation with both plugins results in out shown in Figure 4,

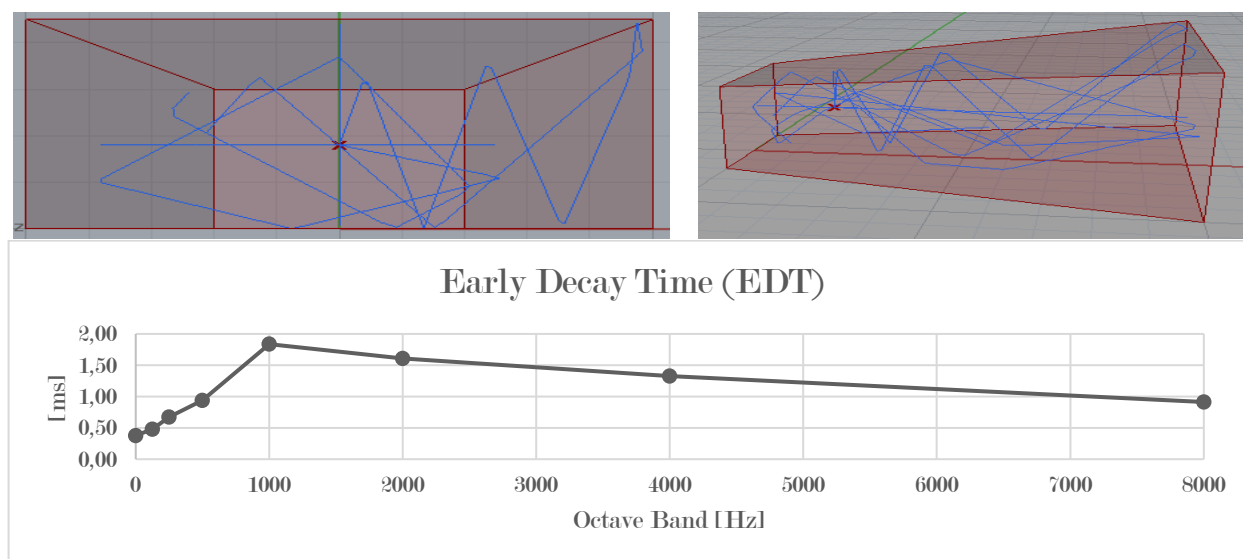


Figure 4: Results from acoustical simulation from Rhinoceros and Grasshopper. The acoustical performance of the room is not only evaluated in EDT, but many other parameters are possible to investigate.

The plugin Pachyderm only contain a few different materials. It is possible to make new materials and define the absorbent and scattering properties. The plugins provide nice simulations but the ability to interoperate lack.

Revit

Revit does not contain acoustic simulation tools. But with the proper information, it could be possible to perform an acoustic evaluation of the rooms in Revit as well. To calculate a simple, but widely used indicator, the reverberation time, you use Sabine's formula, $T = 0,16 \cdot \frac{V}{A}$, where V is the volume of the room and A is the total absorbance coefficient. The volume of the room is already assessable in a 3D Revit model. This is not the case for the absorbance coefficients, but Revit has a material library containing very detailed information, including thermal resistance etc. It seems possible to include acoustical information, either in an explicit sheet of as a part of the library, and calculate this simple formula.

For a more detailed simulation, a link to Rhinoceros or another acoustic simulation tool is necessary. A framework with acoustical performance of a Revit model was made by PhD student Chengde Wu [12]. With this framework, it is possible to use a Revit model to make a frequency analysis. The software is a prototype, but it would be interesting to further develop on the software and make it an integrating part of the Revit environmental analysis.

IAQ

Both Bentley, Graphisoft and AutoCAD have tools to develop a detailed MEP model including pipes and ventilation shafts. Also, they provide heating and cooling tools in order to determine the size of the ventilation system. Often loads like CO₂ are overruled by heating and cooling loads and therefore overlooked. A lot of software is counting people as internal load but only as submitting heat and not CO₂. IES' Apache Loads calculation tool can size the ventilation system in order to accommodate ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality, so a bit attention to IAQ is shown. It would be interesting to include the CO₂-concentration to determine the ventilation strategy, and see if a natural, mechanical or mixed solution would fit the building best.

iDbuild

iDbuild is a one of very few programs which evaluate the IAQ. The tool is developed as a part of a PhD project on DTU [14]. The calculation of the IAQ are based on a European standard prEN 15251, Annex B. In this standard, the IAQ are divided into four classes based on expected percentage dissatisfied. iDbuild is limited to a shoebox geometry with windows on only one wall. It is possible to import geometry from SketchUp, but it cannot cooperate with other software. It is created to provide performance of rooms in the early design phase, where the final design has not been decided yet. iDbuild is therefore not a candidate to further develop simulations of more advanced geometry, but the awareness and calculation procedure of the IAQ could be integrated in other software.

Framework

A framework by Ibrahim Al-Sulalhi are using CO₂-measurements to assess the indoor environment [15]. The data from tracking of temperature, CO₂-concentration and visual comfort are put into the BIM model to locate any future problem in the facility. This approach is only possible at the end of a building project, when the building is finished and applicable for occupants. Then it is possible to use measurement data instead of making assumption as in the design phase with a lower LOD. The framework shows, that BIM can optimize performance of the building from the beginning of the design phase and during the operative and maintenance phase.

According to VOC, the software IAQX can provide information of the decay time of VOC emissions in modelled air zone. The software aims at users with knowledge within this area because different emission models must be selected to simulate. The air zones are simplified into a volume, and it could be interesting to use this software in corporation with a 3D BIM model. This simulation would make it possible to predict how long before the building occupants can use the building. This would require the same expand of the material library as the acoustic case, only with VOC emission data for the different kind of materials.

4. Discussion

The research shows that both acoustic comfort as well as IAQ seems to be overlooked areas of interest when working with environmental performance of BIM models. An explanation for this could be, that the consequences of bad acoustic and IAQ are not directly associated with economy, which still has a major weight in the building process. This is not in line with the holistic view on the three sustainable areas, but still the reality.

The information needed to make acoustic and IAQ simulation is available in the design phases. The LOD is high enough and includes choice of materials, people load and a geometrical 3D model. The obstacle is not missing of information but that most simulation software does not link to a 3D model or that a 3D model does not contain the information needed to make a simulation itself.

IAQ

Another explanation could be that especially IAQ is very hard to predict in the design phase. In this phase the usage of the building is known, but the actual people load, clothing and activity is very variable. Prediction of these is often seen to be incorrect. It is necessary to incorporate IAQ in the design phase, but also to keep investigating the building in the operation phase, because the real use of the building is in this phase.

Because IAQ is subjective and depends on many parameters and actions, it can be hard to predict the IAQ of the building. A nice starting point though is the indoor climate classes as used in iDbuild. Thermal people load is often considered with thermal simulations, so it could be possible to implement the activity and clothing of the people and determine an indoor climate class, based on CO₂-concentration, as well.

CO₂-concentration is often overlooked because sizing HVAC systems often depend on the heating and cooling load. IAQ is more of a detailed simulation, but not the least important to secure the health and wellbeing of the occupants. Anyway, IAQ could be included in the determination of the ventilation strategy.

Acoustic

The research shows that there are many tools to make acoustical performance analysis of 3D buildings. The major challenge is to link the simulation tools to a 3D model, so changes in the geometry easily are updated when doing the simulations. The first step would be to incorporate absorption and scattering coefficient into e.g. the Revit material library and link the 3D model to one of the simulation tools. Furthermore, Revit could incorporate acoustical performance as a part of its environmental performance simulations.

Regarding acoustical simulation in the design phase, the LOD in the start of this phase includes choosing of materials and it is therefore possible to make quite accurate predictions of the acoustical behavior. The simulations can be further detailed as specific products of materials are chosen later in the design phase. As earlier described acoustic is an important factor when working with indoor environment. Even though there is not direct cost regarding this area compared to e.g. solar radiation, it is essential to incorporate the acoustical performance into the building design instead of solving the problem afterwards.

5. Conclusion

Acoustic comfort and IAQ are important to consider when dealing with indoor environment and comfort in a building. Both areas have a great effect on the health and wellbeing of the occupants. Even though the high importance to attention in these areas, the research shows, that there are very few options when doing environmental analysis performance in a BIM environment. A lot of software is available, but there is a gap between the available simulation tools and the 3D BIM model.

Regarding acoustic simulation, it was possible to find multiple tools to make acoustical simulations. Some of them could import geometry from 3D CAD formats, but the obstacle was to import material properties, which was necessary to input manually. This obstacle repeated in the Rhinoceros environment. Acoustical performances were possible, but information as absorption coefficients was not within the database. Acoustic comfort should have more attention in the environmental analysis of building models. For this to happen, simulation tools should be able to link to 3D BIM models. Also, it could be possible to incorporate acoustic

data in the material library of the BIM model and make the acoustic simulation a part of the full environmental analysis. It would suit the authoring companies in the BIM environment to include acoustic comfort in the BIM environment.

IAQ is the same story as acoustic comfort regarding lack of awareness. It is of a more complex size though, and to accommodate good IAQ, many parameters should be satisfied. This report focused on CO₂-concentration and VOC, which was often overlooked, as thermal comfort and dimensioning of HVAC systems are in focus. Assessment of IAQ based on CO₂-concentration is a part of calculation in iDbuild, a PhD project from DTU. The calculation is based on a European standard concerning assessment of IAQ among others and could be integrated in other software as well. The IAQ is also interesting to investigate when deciding on the ventilation strategy. Regarding VOC, the software IAQX was possible to calculate emission for a simple case. By integrating VOC emissions as a part of the material properties in e.g. Revit material library, a plugin like IAQX could be linked and make the same kind of calculations. Then it would be possible to determine the amount of time necessary for the building to be applicable and see the consequences of using cheap materials.

Development in linking simulation tools into the BIM environment is necessary for acoustic comfort and IAQ to become a part of the environmental analysis as they deserve.

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V

Building Information Modeling for Indoor Environmental Performance Analysis – Thermal and Lighting comfort

Thea Hauge Broholt

Abstract

In the last decade there have been developed a large focus on sustainability in the building industry. To reach a sustainable design, it is necessary to change the traditional way of designing, and get architects to cooperate with Engineers and Constructors already from the beginning of the design phase. Thereby as much information as possible is available in the beginning, and informative design decisions can be made with focus on environmental, economic and social aspects. Two methodologies exist which focus on making this cooperation easy; Building Information Modeling (BIM) and Integrated Energy Design (IED). In this paper tools of both methodologies are compared in relation to compatibility with the BIM platform Revit and the information available in the tools about thermal- and lighting comfort. The results show that none of the traditional engineering tools are compatible with Revit. The BIM tool which provides most of the necessary information about indoor climate both in relation to thermal- and lighting comfort is IES Virtual Environment. But another tool that has larger advantages in relation to BIM is Insight360 as analyses can be made directly in Revit. This tool does not provide much information about thermal comfort yet, but it is under development, why it is a good idea to keep updated about new plug-ins for the tool.

Key words

BIM, Sustainability, Thermal Comfort, Lighting Comfort

possible to make cost estimations in relation to the cost of construction and energy use (Krygiel & Nies, 2008). It should be noted that sustainability changes with time, as our ambition level and technical possibilities change. What is considered sustainable today might not be considered sustainable in twenty years from now (Chris Butters, 2014). With BIM it is easy to go back to the model of an existing building and assess if any changes are possible through retrofitting.

In this paper focus will be on Building Information Modeling in relation to indoor climate, focusing on thermal- and lighting comfort. In the following section it is described how tools, for evaluation of indoor environment, are used in the traditional way of working, in IED and in BIM. In section three there is focus on thermal- and lighting comfort, it is given why it is important to be aware of these areas of the indoor climate, and which information the traditional- and IED tools provide in these areas. In section four it is evaluated if any of these tools can be used in relation to BIM. Further five different BIM tools are compared to the traditional- and IED tools to evaluate if they provide enough information to leave out other analyzing tools when using BIM.

2. Indoor Environmental Performance

As people are spending a lot of their time during a day indoors, it is important to create a good indoor climate. In the Danish Building Regulation there are few requirements and recommendations to ensure this. In European Standards, as EN 15251, there are made indoor climate categories based on temperature, air quality, acoustics and more, as guidelines for improving the indoor environment.

In the traditional way of working there exist tools as BSim or Be15, to evaluate if the requirements and recommendations in the Building Regulation are met. These tools need a lot of information to make useful analyses why they are most suitable in the later design stages. As it is shown in Figure 1, when using the traditional design process, not many decisions are made in the early design stages and thereby not much information is available, but analyses should be done, as it is in these stages that improvements are possible.

When using an approach as Integrated Energy Design, there exist simple tools which do not need much information to make analyses of the indoor environment. These tools are very useful in the earlier design stages, to determine how design choices can affect the indoor environment in the end. In IED the tools are used to make “design-frames” for the architect. For example a maximum and minimum amount of glazing per room with a specific orientation, to ensure minimum overheating and enough daylight (Andersen, et. Al., 2009). This information can be used by the architect to design without worrying too much about the indoor climate, because it is already ensured.

With BIM it is possible to design a concept of a whole building, and still make analyses in the early design stage to test and improve the building performance. There already exist tools that are compatible with BIM platforms, which makes it possible to analyze things like lighting comfort, thermal comfort, CFD and acoustics. Information about the building model or the model itself, can be extracted from the BIM platform, and then imported into the analyzing tools. Other tools exist where it is possible to make the analyses directly in the BIM platform. Thereby it is possible to make well-informed design decisions to ensure a good indoor climate (Lim, 2015). The BIM methodology has its advantages especially for architects, as the working process is similar to the traditional one. But for engineers to choose this methodology instead IED it is required that the tools in the BIM platform are as easy and as informative as the tools they are used to. This is what will be explored in the following sections, with focus on thermal- and lighting comfort.

3. Thermal & lighting comfort

3.1 Thermal comfort

It is important to ensure comfortable temperatures, because thermal discomfort is one of most common complaints of occupants. It is hard to satisfy a large group of people, as thermal comfort is subjective, but it is possible to estimate the percentage of dissatisfied (PPD), and how satisfied/dissatisfied occupants will be by the Predicted Mean Vote (PMV) (Fanger, 1973). Studies also show that the temperature can affect the performance of occupants in offices. It can therefore be of interest for building owners to ensure thermal comfort to increase the performance of the employees. Performance increases until temperatures around 21-

22 °C, and decreases at temperatures above 23-24 °C. The peak performance is found around 22 °C (Seppänen, et. Al. 2006). In the Danish Building Regulation (6.2, stk. 1) it is recommended that in offices and similar, the building owner specifies a limit of hours of the year that the temperature can exceed 26 °C and 27 °C. In the standard EN 15251 indoor climate categories is defined in relation to PPD, PMV and operative temperature.

The traditional tool BSim is typically used by engineers to ensure that requirements in the building regulation are met. For thermal comfort the tool therefor provides information about hourly mean room temperature, and the opportunity to calculate hours of the year above 26 and 27 °C. Further it is possible to get information about the hourly mean operative temperature, which is the temperature that occupants will actually feel. It is also possible to get information about the energy consumption for heating and cooling. To get usable results in this program it is necessary to build up a model in the program, assign details about the wall, roof, floor and window components. Further you should add systems as lighting, ventilation, people load and more, with time schedules and details about the different components. All this information is in most cases not available before Construction Development stage in the design phase.

Two tools that are made for IED are iDBuild and Viper. In iDBuild it is possible to get information about operative temperature in relation to the indoor climate categories defined in EN 15251; you get the percentage of time through a year that the operative temperature is within the different categories. It is possible to get information about the PMV and the PPD, which also can be used to evaluate indoor climate categories. Further it is possible to see how many hours of the year that the mean room temperature is above or below a specific temperature, which can be used to ensure that the recommendation in the Building Regulation is met. In iDBuild it is also possible to get information about the energy use for heating and cooling. The inputs that iDBuild need is a simple model of a room with only one window in one wall, a few details about building construction, windows and systems, but mostly on conceptual level. It is possible to analyze how the amount of glazing or the choice of system affect the indoor climate or the energy use of the building. Therefore this tool is suitable for an earlier design stage as schematic design/design development.

Viper for Grasshopper (in Rhino), is a simple tool as iDBuild. From Viper it is possible to get information about the hourly mean air temperature in the room. This can be used to determine how many hours the temperature is above certain temperatures, and thereby evaluate if the recommendations in the Danish Building Regulation are met. Further it is possible to get information about the energy use for heating and cooling. For Viper to provide this information it needs a simple model, it can contain more than one room (different Viper zones), some overall information about the wall construction and window type, and overall information about the systems, as peopleload, setpoints for heating and cooling, and so on. Viper does not provide much information about the thermal comfort, why a new program is under development, this is called ICEbear. ICEbear uses the information from Viper about heat gains from sun and systems to get basically all the information that iDBuild provides.

3.2 Lighting comfort

In Lighting comfort there is often a focus on the use of daylight. The necessary amount of light can always be reached by using electrical lighting, but there are different benefits in using as much daylight as possible. First there is the energy saving when not using more electric lighting than necessary, second studies show that daylight has a positive effect on occupant health and well-being. But with a large amount of daylight comes problems like glare and overheating, therefore lighting comfort is a difficult but very important issue (Osterhaus, 2004). In the Danish Building Regulation (6.5.2, stk. 1) it is recommended that a Daylight Factor of 2 % is reached at working stations in offices. In the standard EN 15251 is a recommendation of illuminance in different types of buildings. It is recommended that this lux-level is reach mostly by daylight if possible.

Different tools which can be used in the early design stages to simulate the amount of daylight in the building are tools like DIVA for Grasshopper, iDBuild, Velux Visualizer and ICEbear. DIVA for Grasshopper provides information as the daylight factor, which can be used to determine if the recommendation in the Danish Building Regulation is reached. Further it is possible to get information about the hourly illuminance (light level that reaches a surface), this can be used to evaluate the daylight in relation to recommendations in the standard EN 15251. It is also possible to get information about the Useful Daylight Illuminance (UDI), to ensure enough daylight and no glare in as much of the occupied hours as possible. In addition it is possible to get the hourly luminance (the amount of light energy reflected from a surface, this is the light we see), and Daylight Autonomy (percentage of hours of the year that the light level is above a specific illuminance). For

DIVA to provide this information it should be specified if it is wished to get it in a specific point or in an area, further information about the building structure and components should be given. ICEbear uses DIVA to provide the same information.

IDBuild provides information about the daylight factor, UDI and Daylight Autonomy, both in a specific point in the room and as a distribution in the room. The inputs for iDBuild are specified in Section 3.1. Velux Visualizer gives information about the luminance and illuminance, these are given on a specific time of the day, on a specific day of the year, which is possible to change. Further Velux provides information about the Daylight Factor, which is typically used to ensure that the recommendation in the Danish Building Regulation is reached. The inputs for Velux is a very simple model, this can be imported from SketchUp or be build up directly in the program. Then the place of the building should be set, and reflectance of surfaces on the inside of the building should be given.

4. BIM for Thermal & Lighting comfort analysis

In this section the traditional engineering tools described in the earlier sections are compared to five different BIM tools. Three of them are IES Virtual Environment (IES-VE), Autodesk Green Building Studio (GBS) and Autodesk Ecotect. These are chosen because a questionnaire in (Azhar & Brown, 2009) showed, that these are the three most used analyzing tools in firms who use BIM. In addition it is chosen to evaluate Design Builder, which is used in a newer comparison article (Lim, 2015). And it is chosen to evaluate Insight360, which is a new tool from Autodesk, which is meant to substitute the two tools; Ecotect and Green Building Studio (GBS).

It is first of all wished to evaluate if it is possible to use the traditional- and IED tools for BIM. This is done by comparing the BIM possibilities in the BIM tools with the traditional tools. In Table 1 all tools are compared in the following categories:

- *Compatible with Revit by gbXML-files:*
GbXML-files are files that contain information about the building, such as information about the site in relation to weather data and orientation and similar, about the building components for walls, roofs, floors and windows, and information about systems as peopleload, lighting, HVAC and so on. Based on this information it is possible to make analyses evaluating the choices, but it is not necessarily possible to make design changes, as this requires a model.
- *Compatible with Revit by 3D model:*
Here it is evaluated if it is possible to import the 3d-model from Revit to the analyzing tool, and thereby make design changes directly in the tool. The disadvantage of these tools is that if changes are made, you have to update the 3D model in the BIM platform every time.
- *Analyses directly in Revit:*
With some tools it is possible to make the different analyses directly in Revit. Thereby the BIM model is dynamic, as design changes are made directly in the BIM environment.
- *Building-level simulation:*
Here it is evaluated if analyses are made on building-level or only on room-level. The disadvantage of making the analyses on room-level only, is that more simulations have to be made for covering all room-types, compared to if all room-types are included in one simulation.
- *Comparison of results*
The possibility of comparing results makes it easy in the early design stages to explore which design choices affect the indoor environment the most both for better and for worse.

Table 1 Overview of tools and their BIM potential

BIM potential										
	BIM tools					Traditional- and IED tools				
	IES-VE	GBS	Ecotect	Design Builder	Insight360	BSim	Viper/DIVA	ICEBear	iDBuild	Velux
Compatible with Revit by gbXML	X	X	X	X	X					
Compatible with Revit by 3D-models	X		X	X	X					
Analyses directly in Revit					X					
Building-level simulation	X	X	X	X	X	(X)	(X)	(X)		
Comparison of results	X	X	X	X	X				X	

Table 1 show that the traditional engineering tools have no BIM potential, as they are not compatible with the BIM environment and it is mostly possible only to make analyses on room-level. All of the BIM tools obviously have BIM potential, but some of them have more advantages than others. Insight360 provided by Autodesk has the advantage, that it is possible to make analyses of indoor climate directly in the BIM environment. Thereby the building model is automatically updated when making changes for analyses, and it is easier to avoid mistakes. All of the chosen BIM tools and iDBuild provide the possibility to compare the results from the analyses.

As none of the traditional tools has BIM potential, it can be interesting to evaluate if these tools can be substituted by some of the BIM tools. But for this to be possible, the BIM tools have to provide the necessary information. Therefore the different BIM tools are compared to the traditional tools, in Table 1, in the following categories in relation to thermal comfort:

- *Room air temperature:*
Here it is evaluated if the tools provide an hourly mean air temperature. This is typically used in the traditional tools, as it is possible to evaluate if the recommendations in the Danish Building Regulation about maximum hours above temperatures of 26 and 27 °C are met.
- *Operative temperature:*
This is the temperature that occupants actually feel when taking draft, humidity and thermal radiation into consideration. With the operative temperature it is possible to determine the indoor climate categories defined in the standard EN 15251.
- *Hours above/below certain temperature:*
Some tools provide the information of how many hours of the year that the mean air temperature exceeds certain temperatures. This is useful when wanting to ensure that the recommendation in the Danish Building Regulation is met. Further information is available on hours below certain temperatures. This can be of interest for building owners in relation to performance of his/hers employees. As mentioned earlier the performance increases until temperatures around 21-22 °C.
- *Energy use for heating/cooling:*
This has not much to do with comfort, but it is nice to know if wanting a sustainable design in the end.
- *Predicted Mean Vote/Percentage of Dissatisfied:*
Some tools provide information about how occupants will assign their thermal comfort level (PMV), and how big a percentage of the occupants that is predicted to be unsatisfied with the

temperature (PPD). This information can be used in the same way as Operative temperature, to evaluate which indoor climate category from the standard EN 15251, the building lies within.

In relation to lighting comfort the following categories are considered:

- *Daylight Factor:*
The daylight factor is essential when wanting to ensure that the building meets the recommendation in the Danish Building Regulation. As mentioned it is recommended that the daylight factor is above 2 % on workstations in offices.
- *UDI:*
The Useful Daylight Illuminance provides information about how much time of the year or the time of occupancy that there is enough daylight in the room (the illuminance is above 200 lux), without risk of glare (the illuminance is below 1000lux).
- *Luminance:*
This is describing how much of the light energy which reaches a surface (illuminance) that occupants will actually see. Some traditional tools provide this information, but it is not necessary for ensuring that any recommendations are met.
- *Illuminance:*
The standard EN 15251 recommends a lux level in different types of rooms/buildings. The illuminance are used to ensure that these recommendations are reached.
- *Daylight Autonomy:*
This can be useful in the same way as the UDI. As the daylight autonomy describes how much of the time the illuminance is above a certain level. Thereby enough daylight can be ensured.

Table 2 Thermal and Lighting comfort analysis basis

Thermal Comfort analysis basis									
	BIM tools					Traditional- and IED tools (thermal)			
	IES-VE	GBS	Ecotect	Design Builder	Insight360	BSim	Viper	iDBuild	ICEBear
Room air temperature	X		X	X		X	X		X
Operative temperature				X		X		(X)	(X)
Hours above/below certain temperature	(X)		(X)	X		X	X	X	X
Energy use for heating/cooling	X	X	X	X	(X)	X	X	X	X
Predicted Mean Vote	X		X	X				X	
Percentage Dissatisfied	X		X	X				X	
Lighting Comfort analysis basis									
	BIM tools					Traditional- and IED tools (lighting)			
	IES-VE	GBS	Ecotect	Design Builder	Insight360	Velux	DIVA	iDBuild	ICEBear
Daylight Factor	X		X	X	X	X	X	X	X
UDI	X						X	X	X
Luminance	X					X	X		
Illuminance	X		X	X	X	X	X	(X)	
Daylight Autonomy	X		X		X		X	X	X

As earlier mentioned the BIM tools have to provide at least the same amount of information as the traditional engineering tools for the tools to be useful. Table 2 makes it easy to compare the information available in the different tools.

For thermal comfort analyses it is seen that three of the BIM tools provide necessary information and even more in some cases; IES Virtual Environment, Ecotect and Design Builder. Design Builder provides the most information of all. Green Building Studio is a tool that focuses more on the energy consumption and economic aspects of sustainability why it does not provide information about comfort. Insight360 does not provide information about thermal comfort either. But it is a fairly new tool and it is under development. It is the plan that the information available in Green Building Studio and Ecotect should be provided in Insight360, why it is a good idea to keep updated about this tool.

For lighting comfort IES Virtual Environment provides most information, but Ecotect and Insight360 also provide some useful information. Design Builder does not provide much information, but enough to ensure that recommendations in the Danish Building Regulation and the standard EN 15251 are met. Some might think the UDI is useful information to ensure that there is no risk of glare.

Some of the tools are marked with only a “(X)”, the reason is, that Insight360 provides the heating and cooling load in the building, and from this it gives an idea of the heating/cooling energy use. As IES Virtual Environment and Ecotect are providing hourly information about the mean air temperature, it is assumed that it is also possible in some way to determine the hours above/below certain temperatures. In iDBuild and ICEbear it is possible to see how much time of the year the thermal comfort in relation to operative temperature is within the different indoor climate categories defined in the standard EN 15251, but not the operative temperature on an hourly basis.

5. Discussion

Through this paper traditional engineering tools have been compared to BIM tools in relation to the possibility to import information from Revit and the information available in the tools regarding thermal- and lighting comfort. But there are other things to consider when highlighting the advantages and disadvantages of the different tools. For example you should consider how fast the tools are making analyses. Time is a very important factor in a design phase when decisions are being made; it is a great advantage if it is possible to make very fast calculations when meeting with the architect for example. Another issue is the user interface, is it easy to follow or should the engineer use a lot of time to figure out how to even get the results out of the program? And when considering the BIM potential it is essential to consider in which design stages the tools can be used.

Table 3 Tools that are suitable for the different design stages

	Pre-design	Schematic Design	Design development	Construction documentation
Activities in this stage	Site-analysis	Design on conceptual level	Final design	Documentation (does the design meet requirements?)
Suitable tools	Revit it self	IES-VE, GBS, Ecotect, Design Builder, Insight360, Viper/DIVA, iDBuild, ICEbear Velux	IES-VE, Ecotect, Design Builder, Insight360	Design Builder, BSim, DIVA, ICEbear

In Table 3 it is seen that most BIM tools can be used through all design stages. In Revit it is possible to make site analyses both in relation to how the sun is distributed and how other buildings are making shadows, and in relation to the weather conditions in general in the area and so on. All tools except BSim are suitable in the schematic design stage, as not many inputs are necessary for making an analysis. In the design development more details should be added to the analysis model, here are the suitable tools the ones where analyses can be made on the 3D model of the whole building. For construction documentation, tools like BSim is widely accepted as a tool for documentation of energy use and indoor climate, but other tools provide the same information.

Through the paper focus has been on the BIM platform Revit, as this the most used one in Denmark. But it should be noted that there are other platforms as Bentley, ArchiCAD (also provided by Autodesk), Tekla structure and others. (Eastman, 2011) gives an overview of the different platforms with their strengths and weaknesses. In some of these platforms, like ArchiCAD, there are many of the same export/import possibilities as in Revit, why some of the tools discussed in this paper, can be compatible with these platforms too. Therefore it can be a good idea to investigate which platforms the different tools are able to import information from. This information is almost for all tools available on their official website.

As it is described in the introduction, there are many things to consider when wanting a sustainable building; environmental, economic and social aspects. Information about environmental and economic aspects is available in most of the tools described in this paper. There is especially focus on these aspects in tools as Green Building Studio and Insight360. Further the social aspects involve the indoor climate, in this paper there have been focus on thermal- and lighting comfort, but it should be noted that there are many other aspects which should be evaluated to reach sustainability, for example acoustics, moisture, air quality and so on.

6. Conclusion

In this paper two types of tools are compared in their compatibility with Revit and the information available in the tools about thermal- and lighting comfort. The two types of tools are; traditional engineering tools used in Integrated Energy Design and tools for BIM. This comparison is relevant, as some information about the indoor climate should be available in the early design stages, to ensure a good indoor climate in the end. This information is provided in the traditional tools (BSim, iDBuild, ICEbear, DIVA/Viper and Velux Visualizer), why it can be of interest to evaluate if these tools can be used for BIM. The evaluation showed that this is not possible, as none of the tools are compatible with BIM platforms in any way. Therefore it is interesting to compare BIM tools with the engineering tools to see if the BIM tools provide the necessary information, so analyses in traditional tools can be avoided. When evaluating the tools in relation to the information about thermal- and lighting comfort IES Virtual Environment provides a lot of information in both areas, why this seems like a very strong tool. The only disadvantage is that it is a stand-alone program, so when making analyses and changes in the program, the model in the BIM environment has to be updated manually every time. It was seen that the BIM tool with the best BIM potential is Insight360 as it is possible to make the analyses and changes directly in the BIM environment. In relation to thermal comfort this tool do not provide much information, but most of the useful information about lighting comfort is provided, maybe UDI would be nice to add to the tool. Insight360 is a quite new tool and is under development, as it is the idea that it should provide the information available in Green Building Studio and Ecotect. It would be a good idea to keep updated about new add-ins for this tool, information about thermal comfort might be added.

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VI

Building Information Modeling for Indoor Environmental Performance Analysis – Acoustic and Lighting Analysis

Nathalie Østerbye Hansen

Abstract

The sustainable development has been supported by development within science and technology. BIM is one of the technologies that support the sustainable development. Through an investigation of possibilities with BIM, the available tools for acoustic and lighting performance has been found. It showed not to contain tools for analyses of acoustic performance, but the tool EASE has the possibility of exporting and importing between the software and Revit including geometry, acoustic information and materials. CATT also had the possibility of exporting and importing information, but only geometry. For lighting performance analyses, Revit showed to have its own tool, Insight 360, which is cloud-based in Green Building Studio. Here it is possible to make analyses of the daylight for the whole building for many of the common analysis parameters.

Key words

BIM, Sustainability, Acoustic, Lighting Analysis

1. INTRODUCTION – BIM AND SUSTAINABILITY

Sustainability development is a quickly developing concept, dealing with the connection between social, economy, and natural systems. “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (World Commission on Environment and Development, 1987). It finds that when balancing the 3 parts of the concept the design solution will get better. The concept tries to find a solution which has no, or minimal, negative impact on the environment, but with a positive effect on the social and economic activities (Krygiel and Nies, 2008).



Figure 1.1 The Triple Bottom Line

Social responsibility: When designing a building, a code of ethics is mandatory in the responsibility to protect life. Normally is this responsibility within the lives of the occupants in building respectively. But as our choices also make an effect on human life elsewhere than this building more aspects has to be taken into account. As materials and products of the building is manufactured in various of places. These places can also be affected by the construction of the building, as people can get exposed to toxics to during the manufacturing process. Another factor which should be concerned is the health and well-being of the occupants of the building. They can be influenced by noise, temperature, humidity, access to fresh air, daylight, view of natural environment, and the ability to control the environment. These parameters can cause physical and psychological effects, short or long term (Krygiel and Nies, 2008).

Natural environment: 40 % of the Danish energy use comes from buildings. This makes it important to reduce the energy use as the consumption by buildings results in pollution, ozone depletion, and global warming, which causes health effects for living species. In addition, are many building materials either non-renewable, e.g. plastic or steel, or used quicker than produced, which pollute or remove the containment of the natural products. Further is water used for toilet flushing in an amount that could have provided every person in the world with clean drinking water (Krygiel and Nies, 2008).

Economic effects: Traditionally is the economic aspect one that has driven most corporate decisions. Building green has often an increased cost as materials and products often has an increased priced. But designing sustainable has seen to have some cost benefits as the return of investment times is quickly being reduced. Many of the strategies used to create a healthier space reduce the operational cost of the building. Though money can be saved, the savings are not remarkable compared to the productivity gains of the workforce (Krygiel and Nies, 2008).

A critical role of supporting a transition towards the sustainable development is innovation within science and technology. BIM is one of a sustainable technology, which can be used to design and monitor a project’s digital information during its lifecycle. The technology offers the potential to transform the conventional project delivery approach (Eastman *et al.*, 2011). BIM can be defined as a set of technologies, processes and policies enabling multi-stakeholders to collaboratively design, construct and operate a facility.

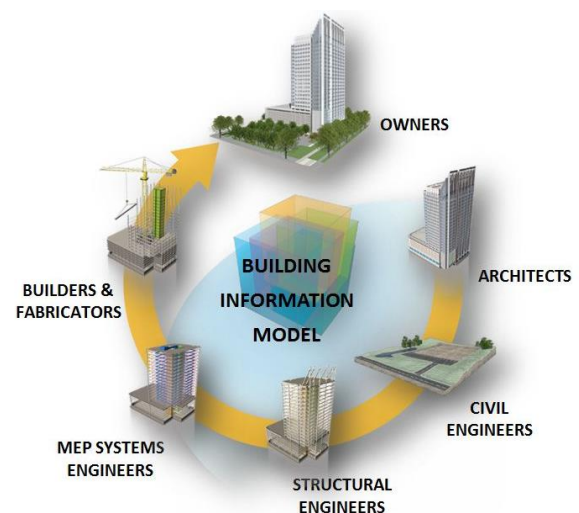


Figure 1.2 BIM Lifecycle view

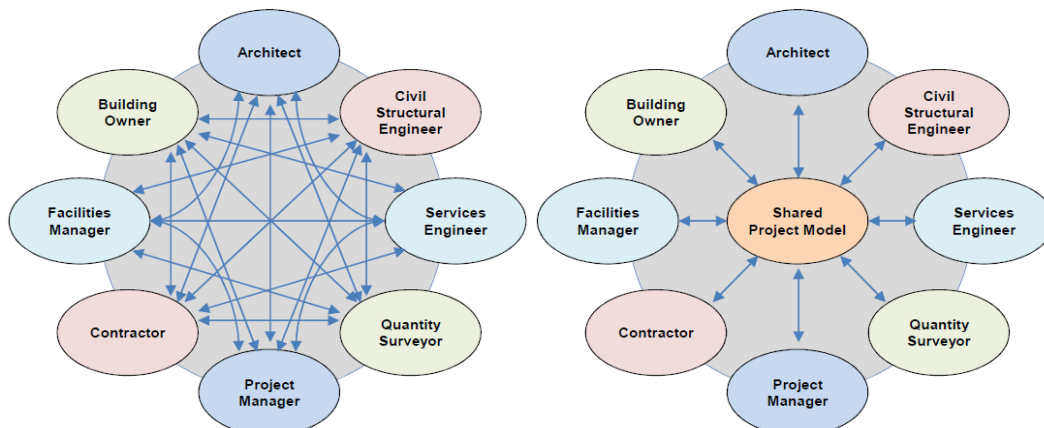


Figure 1.3 Left: Traditional method, Information "Chaos". Right: BIM, Shared project model.

The The concept of BIM is often misinterpreted as a piece of software, which also is a necessary part of the process, but refers to more than that. BIM is information about the whole building and design documents stored in an integrated database as seen in Figure 1.3. All of this information is parametric and thus interconnected. This means that any changes of an object in the model will be changed through the rest of the parts and views of the project. Thereby will the information be distributed out to all involved. BIM models can be used holistically through the design and construction process and has thus changed the way that designers and contractors look at the entire building process (Krygiel and Nies, 2008).

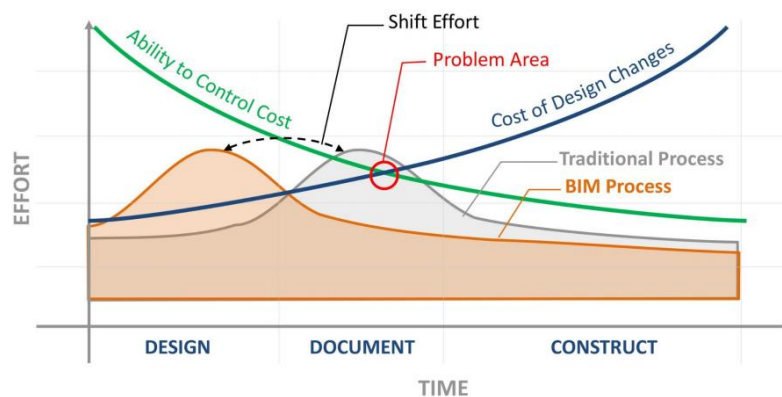


Figure 1.4 Ability to Control Cost and cost of Design Changes through the phases of the building. Comparison of Traditional Process and BIM Process.

In the early design phase, many essential decisions have to be taken, which can affect the functional quantities, the performance of the building, aesthetics, and the relationship of the building with the natural environment and climate. At this stage the possibility of making changes are high and the cost of these changes are low, as seen in Figure 1.4. But this changes through the phases and the cost of changes increase while the possibility of making changes decrease. BIM makes it possible to make analysis of the early design concepts in terms of e.g. energy analysis. Thereby will the effort be shifted to the early stages where the design is still on the drawing board. (Çavuşoğlu, 2015).

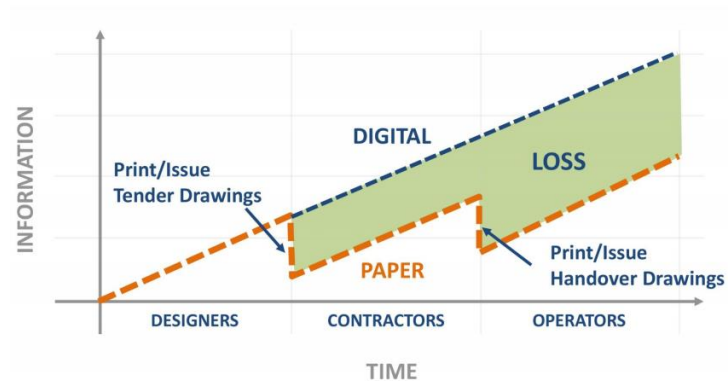


Figure 1.5 Loss of information through the phases.

An advantage of BIM is e.g. the possibility of making performance of the indoor environment based on the created model in the software. This insures that no information is lost when making an analysis of the indoor environment. Traditionally, a model is created in a software for the kind of analysis, which means that there is no connection between the models. Thereby is various models made, making it easy for information to get lost and differences between the models is seen. BIM removes these uncertainties and lost in communication between involved areas of competences by having one digital model, which is used throughout the whole process, see Figure 1.5.

With BIM, a parametric 3D model can be created, which is used to autogenerate the traditional building abstractions like plans, sections, elevations, details, and schedules. Drawings are thereby interactive representations of the model and changes in one of the model-based framework views will be propagated to all other views of the model. Thereby do the BIM-based system differ from a CAD-based method, where each view is drawn separately with no relation between the drawings. The CAD-based method is simply just a collection of the manually generated files, whereas the BIM model has the ability to generate the files based on the model. In addition, does the 3D representation of the model make it possible to make simulation of the building and its components. This makes it possible to predict collisions, show environmental variables on different building designs, and calculate material, and time quantities (Krygiel and Nies, 2008).

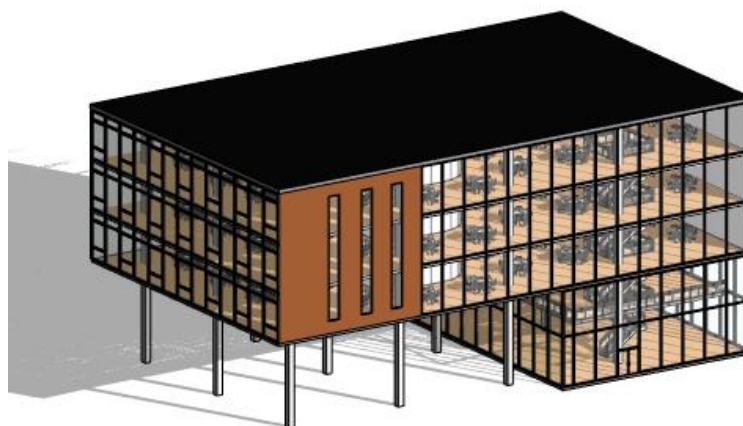


Figure 1.6 Office building made in Revit

One of the programs that supports BIM is Revit from Autodesk. Revit is a program that supports the BIM-workflow from concept to construction. With Revit, tools will be provided for architectural drawings, ventilation technology, electric technology, VVS technology, building technology, construction, and possibilities of coordination between the different disciplines (*Revit-familien | BIM-programmer | Autodesk, 2017*). Revit is a tool often used in Denmark in the building industry, which makes it interesting to investigate

the possibilities with the software. Other programs that support BIM include the Bentley community. The potential of Revit as a BIM tool will in this paper be investigated further in relation to the indoor environment.

2. INDOOR ENVIRONMENT PERFORMANCE

The opportunities for improving building environmental performance occur at the early design phase or pre-construction stages as the possibility of making changes at this point is best. (Azhar and Brown, 2009). BIM-based simulation is seen as very crucial during the pre-design stage in order to develop a sustainable building design. It makes it possible to extract building information directly from a modelling as developed by the architect for various building performance analyses. These forms of performance could be such as solar study, daylighting, building energy use, and CFD. With a simultaneous process between architectural design development and building indoor environmental performance studies a sustainable design will be achieved in a more time and cost effective matter. The challenge is though that the implementing of BIM-based sustainability analysis is missing well-defined transactional process models and practical strategies for information to get integrated. Even though this has been researched there is no standard guidelines for BIM-based modelling and especially not for the indoor environmental performance evaluation. Therefore is still more effort needed to develop framework and guidelines for BIM-based design and analysis process in order to achieve a comfortable indoor environment and sustainable development (Lim, 2015).

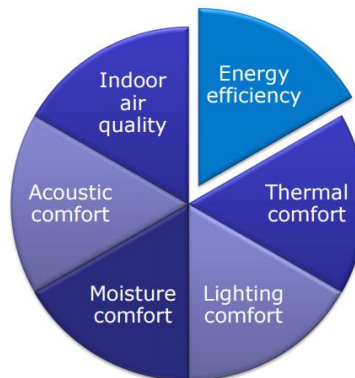


Figure 2.1 Building Information Modeling for Indoor Environmental Performance Analysis

At the moment, some analyses are possible to do in the program and others can be done by using add-ins for the program or exporting to others. Revit has a built-in analysis tool for the indoor environment, where it is possible to make energy simulation by generating a model. This makes it possible to make an analytically model in Insight 360, which is generated in Green Building Studio (GBS). To get a better understanding of the possible analyses to perform in Revit a study will be made of the possibilities within the program and/or with additional add-ins/methods. In this study the analysis of the indoor environment performance will be based on 2 of the areas listed in Figure 2.1, acoustic comfort and lighting comfort.



Figure 2.2 Acoustic and lighting comfort

Acoustic and lighting is areas depended on the building design and materials used in the building. Thus, are they very important to work with in the early design phase as they can by difficult to work with later in the process and would increase the cost of “tinkering”. Thereby is it important to have the right tools to makes these investigations. The potential of BIM for acoustic and lighting performance will be investigated for available tools at the moment. The required parameters which the program should be able to calculated in relation to the demands will be highlighted and the possibilities will be compared to normally used tools. In

addition, if possible within Revit a small example of acoustic and lighting performance with Revit will be made.

3. ACOUSTIC COMFORT

When making analysis of the acoustic comfort some parameters are important to look at in order to create a good acoustic environment. Overall should buildings be planned, designed, constructed, and arranged so the acoustic conditions satisfy the users. This is both in terms of the building acoustic and the room acoustic. When analysing the acoustic comfort in a room some parameters are calculated. Dependent on the use of the room different requirements is set up for the performance.

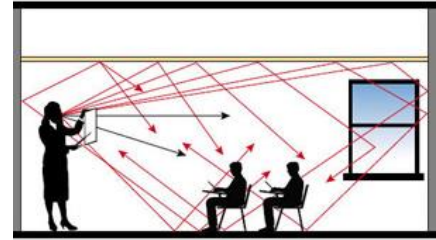


Figure 3.1 Room acoustic

3.1. Acoustic analysis parameters

- Reverberation time (Sabine and Eyring): The time it takes for the sound to be reduced by 60 dB.
- Early Decay Time (EDT): Perception of reverb by the occupants in the room in s.
- Speech Transmission Index (STI): Describes how the speech in different variations a room is perceived and is expressed as a number between 0 and 1.
- Deutlichkeit (D50): Describes the clarity of the speech expressed in %.
- Clarity (C_{50} , C_{80}): C_{50} (50 ms early time) is used for speech or stage evaluation. C_{80} (80 ms early time) is typical for music application. Both in dB
- Sound strength (G): Describes subjective level of sound in dB.
- Center Time (T_s): Describes the spatial impression and clarity of music.
- Ray detection: Predicts how the room responses to sounds and how it is distributed. It is used for designing room geometries.

3.2. Normally used tools for acoustic analysis

CATT-acoustic is one of the leading software packages for geometrical acoustical prediction. The software makes it possible of modelling rooms in the program. But also, use other programs which are suited for the geometrical modelling and import it into the program. With CATT, it is possible to make changes of materials in terms of technical information of absorption and scattering coefficients, and adding sound sources. It gives the tools that is needed for making acoustic analyses and insuring the acoustic comfort (CATT-Acoustic v9.1, 2017).

EASE is another leading software for making acoustic analyses. As CATT-acoustic it is possible to make acoustical predictions and has many of the same features as CATT. In differ to CATT it is possible to import geometrical models from CAD directly into the program. Thereby it is easy to import and export between a CAD software and make a continuous analysis of the design and continue the work based on the design (Features - EASE - Enhanced Acoustic Simulator for Engineers, 2016).

3.3. BIM for acoustic analyses

In Revit, there is not tool implemented to perform acoustic analyses at the moment. Earlier it was possible to use the tool Ecotect, which could perform analyses of the Revit model by exporting/importing the model. Including acoustic analyses. But as the maintenance stopped and new licenses was not possible to get, Autodesk started to implement the tool in Revit, Insight 360. Though it is now possible to perform e.g. daylight analyses with Revit, the acoustic analysis has not yet been implemented. As an add-in in the Autodesk environment, Acoustamo can be added in Dynamo and ray detection can be performed for conceptual Acoustic Analysis, but tge tool do not satisfy analyses of the acoustic performance (Acoustamo Released! | andreaarch, 2015).

In Revit, there is the possibility of exporting the model as a CAD file. This can be opened into the EASE software, or CATT software if the geometry is converted using the DXF2GEO converter. For EASE, it is possible to move back and forth easily between EASE and external drawing tools to maintain specific acoustic information and relationship trough the transfer (Powerful integration with third-party CAD programs, such as Autodesk AutoCAD and Trimble SketchUp - EASE - Enhanced Acoustic Simulator for Engineers, 2016). In this way, it is possible to import and export between two software in order to perform acoustic analyses on the building design and continue the further work on the model in Revit. Thereby is there a focus on the fluent data exchange between the programs. But for CATT some information is lost as it is only possible to exchange

the geometry using the DXF2GEO converter. This means that acoustic information, such as absorption and scattering coefficients, and materials are not possible to exchange and has to be set up within the software. This gives some limitations and extra work if the analysis is made using CATT in combination with Revit.

3.4. Comparison of tools

In order to compare the different tools for acoustic analyses, the analysis parameters have been listed in Table 3.1 with BIM and for normally used tools.

Description of symbols:

X possible within the software

(X) possible to export/import between BIM and software

(x) possible to export/import some information between BIM and software (loss of information).

	Tools with BIM			Normally used tools	
	Acoustamo	CATT	EASE	CATT	EASE
Reverberation time – Sabine		(x)	(X)	X	X
Reverberation time – Eyring		(x)	(X)	X	X
Early decay time (EDT)		(x)	(X)	X	X
Sound pressure level (SPL)		(x)	(X)	X	X
Speech transmission index (STI)		(x)	(X)	X	X
Deutlichkeit (D ₅₀)		(x)	(X)	X	X
Clarity (C ₅₀ , C ₈₀)		(x)	(X)	X	X
Sound strength (G)		(x)	(X)	X	X
Center Time (Ts)		(x)	(X)	X	X
Ray detection	X	(x)	(X)	X	X

Table 3.1 Comparison of different tools for acoustic analysis with BIM and normally used tools.

4. LIGHTING PERFORMANCE

In order to create a good daylight in a building some parameters can be calculated to get a picture of the lighting distribution in the rooms. The level of lighting should satisfy the activity and work the room is used for. As the use of rooms are different there are different demands for the lighting level. The level of daylight the should be above 2 % according to the Danish Building Regulation. To fulfil the demand for a 2020 building it should be above 3 %. In addition, does the demand claim that the lighting should not cause glare and rise the chance of overheating the room. Meaning that the rooms should not be lighted unnecessarily.

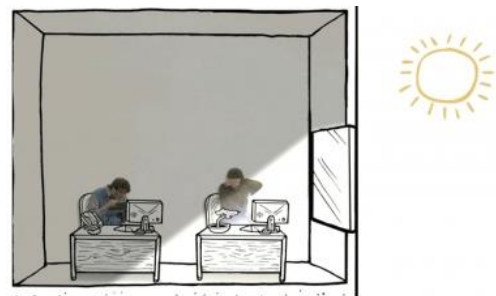


Figure 4.1 Light Distribution & Glare

4.1. Daylight analysis parameters

- Illuminance: Is the amount of light energy emitted or reflected from an object in a specific direction and is the only form of light that is possible to see. Luminance is measured in candela per square meter (cd/m²).
- Daylight factor (DF): Is calculated under overcast sky condition. It is a ratio between the horizontal work plane illumination indoor and by the horizontal illumination on the roof of the building and then multiplied by 100. It is given in percent.
- Luminance or light level: Is the amount of light energy reaching a given point on a defined surface area, in lux.
- Useful Daylight Index (UDI): Percentage of time the lighting level is between the thresholds of illuminance between 100 lux and 2,000 lux compared to the total hours.
- Daylight Autonomy (DA): Is a percentage of annual daytime hours that a given point in a space is above a specified illumination level.

4.2. Normally used tools for lighting analysis

Velux daylight visualizer is a commonly used tool when it comes to simulation of the daylight. It makes it possible to render the different daylight parameters for visualization of the distribution in the room. Room

geometry, windows, doors and roof is made within the program. It is then possible to define materials and add furniture in the room to make more realistic analyses.

DIVA in Rhinoceros Grasshopper has many of the same features as Velux daylight visualizer has. But in DIVA it is possible to make more complex geometries and calculate the daylight by visualization. In addition, it is possible to get calculated results by digits and thereby it is possible to use the results for further calculations and analyses.

4.3. BIM for lighting analysis

Lighting analyses is a part of Revit in Insight 360. Here it is possible to make the same analyses as in normally used tools. The results from the calculation can be found in Revit Insight 360 or in the Green Building Studio (GBS). Illustration of the daylight calculation can be shown in a Lighting Analysis model inside Revit and it is possible to see the results and compare them to the building design. Thereby it is possible to make calculation on the full building and not only on room level. In GBS the results are rendered into pictures which can be analysed. In differ to normally used tools the Daylight Factor and the Useful Daylight Index cannot be calculated by selection in a box. But it is possible to put up a daylight factor sky, which can be used for calculation of DF. UDI can be calculated by setting up a threshold in the lighting settings and in this way, get an estimation of the percentage of useful daylight.

Another way to analyse the daylight of a building is to export the 3D model from Revit into Velux daylight visualizer or IES – FLUCSDL. In FLUCSDL it is possible to perform point-by-point analysis to determine daylight levels within rooms, or groups of rooms. The software can determine lighting levels, daylight factor and makes threshold analyses (IES - FLUCSDL, 2015).

4.4. Comparison of tools

In order to compare the different tools for lighting analyses, the analysis parameters have been listed in Table 4.1 with BIM and for normally used tools.

Description of symbols:

X possible within the software

(X) possible to export/import between BIM and software

(x) possible to export/import some information between BIM and software.

	Tools with BIM			Normally used tools.		
	Revit – Insight 360	GBS	FlucSDL*	Velux daylight visualizer	Velux daylight visualizer	DIVA
Illuminance	X	X	(X)	(X)	X	X
Daylight factor (DF)			(X)	(X)	X	X
Luminance			(X)	(X)	X	
Useful Daylight Index (UDI)				(X)	X	X
Thresholds	X	X	(X)			
Daylight Autonomy	X	X		(X)	X	X
Sky conditions:						
Overcast	X	X		(X)	X	X
Intermediate	X	X		(X)	X	X
Sunny				(X)	X	X
Clear sky	X	X				X
Daylight factor sky	X	X				

Table 4.1 Comparison of different tools for lighting analysis with BIM and normally used tools. * Sky conditions could not be found outside the FlucSDL software.

4.5. Small example of lighting analysis

After making a building in Revit with location and materials a lighting analysis can be made. In order to create a lighting analysis in Revit the lighting tap under Analyse and Insight is simply selected.

This will bring a window with the possibility of running a new analysis or selecting previous analyses. By running a new analysis, a new window will pop up with Lighting analysis in the Cloud. The type of analysis is now selected.

In this example, an Illuminance Analysis is selected for all of the levels in the building. The environment is then selected with a sky model and a time for the calculation. Some Illuminance settings should also be made, by defining the unit of the calculation, the plane height of the analysis, grid size and the threshold, which are used in the Room and Floor Schedules. The threshold can be used to get a picture of the useful daylight index. Next is just to check the box in the bottom to get an email when the analysis is done, then Start Analysis and wait for the results.

When the analysis is done, the Lighting tap is yet again selected. This time a new analysis is not selected, but the analysis just made that will be showed in the box.

After making the lighting analysis a new 3D view and new levels will appear. In these it is possible to show the results from the calculation. The results can be set up dependent on the type of analysis by editing the display style of the analysis in the properties. It is now possible to see the lighting distribution on the calculated floor levels and the legend will show the values and units of the values as seen in Figure 4.3.

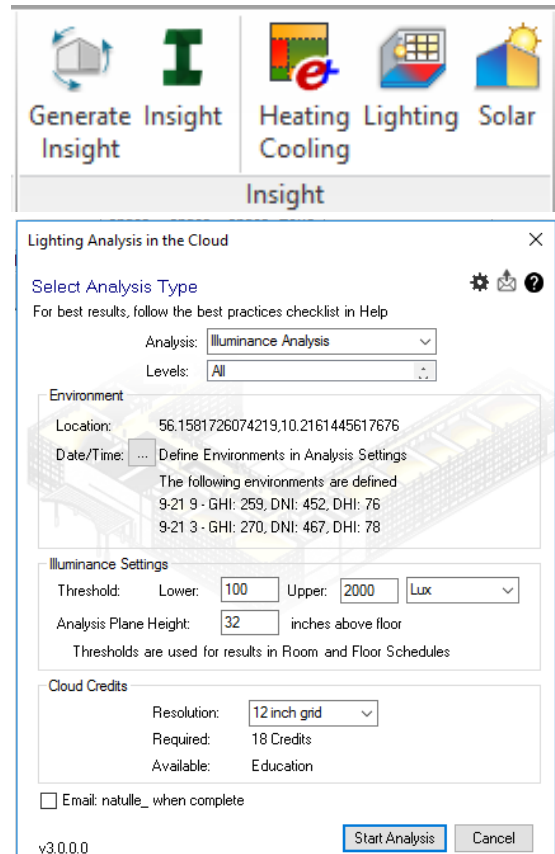


Figure 4.2 Window for selection of lighting analysis type.

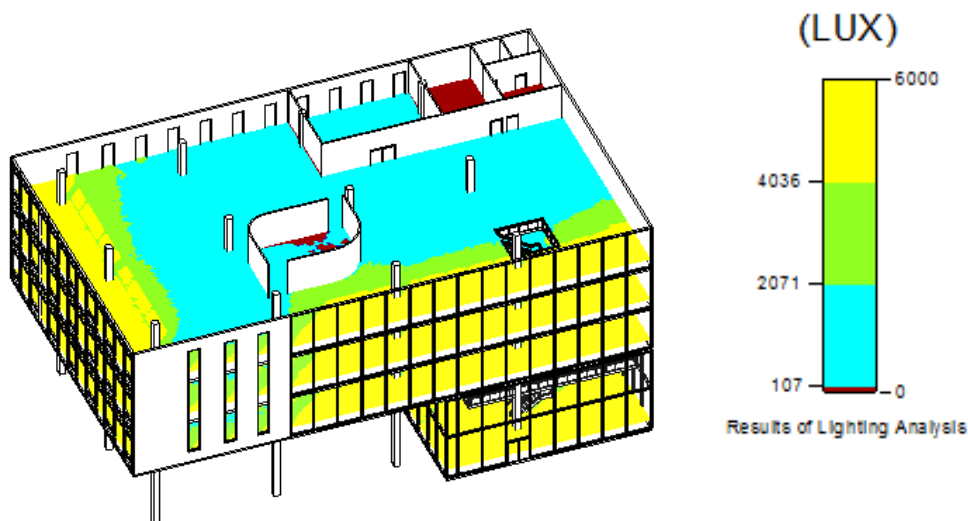


Figure 4.3 Example of lighting analysis in Revit - Illuminance

5. DISCUSSION

As seen through the investigation of BIM tools for acoustic and lighting analysis there is still need of some improvements in order to perform the analyses within the BIM environment. Acoustic analyses are at the time not possible to make inside the BIM environment and increase the time consumption for analyses in the early

design phase as it is not possible quickly to change between the type of analyses wanted to perform. This is due to the time and loss of information when exporting and importing between different tools. Thereby will changes of the building design be more difficult to make as the building design has to be transferred back and forth when new design opportunities have to be made.

Even though lighting analyses is possible in Revit and it has a lot of opportunities when analyses have to be made for at large building, something is still missing. The tool still needs some more parameters to analyse and a more intuitive way of making daylight factor analyses. Due to the cloud-based method of making analyses in Revit it takes a lot of time and many analyses are lost due to bad or loss of internet connection. This takes a lot of time and can be very frustrating as the analyses itself takes some time and in some cases the analysis is lost right before it where supposed to finish. If this instead is made as an implemented tool in Revit or if it just paused the calculation when the internet connection was bad, it would save a lot of time and the calculations would be more efficient.

Having these things pointed out, the possibilities with BIM compared to traditional approaches can give the shift illustrated in Figure 1.4. By having a shared model as in Figure 1.3, analyses of acoustic and lighting could be made when the building is being designed in BIM. BIM provides coordination between industries, which makes it possible to see how other people involved in the project change and adapt their work, and how it affects e.g. acoustic and lighting. It would make it possible to make analyses of the exact design with the materials used. E.g. could the daylight be analysed in the software and based on this analysis artificial lighting could be made. The same model is therefore used for investigation of the correct number of light sources and where to put them in order to provide exactly what is needed. Thereby it would ensure that no information would get lost doing the shift and changes in the building design can easily be analysed again. In terms of acoustic, would it be easier to perform acoustic analyses of the building design as limitations is seen at the moment. It would support the decision-making of the design and ensure that the acoustic specifications are not being lost through the processes. Results from analyses can thereby be maintained within the software and easily be accessed. Continuous analyses can be made as the building develops and effects of changes can quickly be investigated in other disciplines. These point of views supports that BIM would make it easier in the long run to make choices and finalize decisions earlier in the design process compared to traditional approaches.

6. CONCLUSION

Though this investigation of BIM the possibilities of the tool has been showed for the indoor environmental in terms of acoustic and lighting comfort. The investigation showed that the tools is still under development as a full tool for analyses of acoustic has not been implemented in the software yet. Acoustic analyses are at the moment not possible to make within Revit, but there is the possibility of exporting and importing information to tools such as EASE and CATT. EASE gives the possibility of sharing geometry, acoustic information and materials between the tools, while CATT only can transfer geometry. In terms of lighting analyses in Revit, the Green Building Studio provide a tool to make cloud-based analyses, which can be showed in Revit. Thereby can changes easily be evaluated with the software, but still needs some development for some parameters.

The ability of making analyses within the BIM environment of acoustic and lighting support the change of the traditional approach of working with buildings from idea to the final handover. By having a shared model as BIM, it is possible to shift the effort to the early design phase and analyse the design when availability of making changes are highest. It would make it easier to make choices and finalize decisions earlier in the design process compared to the traditional approach.

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VII

Building Information Modeling for Indoor Environmental Performance Analysis – Thermal Comfort and Moisture

Christine Nielsen

Abstract

Indoor environmental performance can consist of many things, but in this assignment, the focus will be on thermal comfort and moisture. A thermal analysis consists of an evaluation of the temperature in a room, but an analysis of how the thermal environment is perceived by the occupants is called a thermal comfort analysis. A thermal comfort analysis is more complex, because it is effected by a lot of parameters including the moisture in the room. There are several analysis tools available, connected to Revit, that can make a thermal analysis, but not yet a tool that is able take all parameters into consideration and make a thermal comfort analysis. This assignment is made for the purpose of getting updated within the field of BIM and sustainability.

Key words

BIM, Sustainability, Thermal Comfort, Moisture, Analysis Tools, Design Process

1. INTRODUCTION

This assignment takes hold of two very debated topics: Building Information Modeling (BIM) and sustainability. These are two very modern topics but is also interpreted very broadly in the building industry. BIM is a methodology and to use BIM, some people thinks that it is necessary with an actual model of the building, maybe because of the name. Others think that an excel sheet with data of the building that is automatically shared can be interpreted as BIM. However BIM is interpreted, it has the purpose to facilitate the necessities in the AEC industry (Çavuşoğlu, 2015).

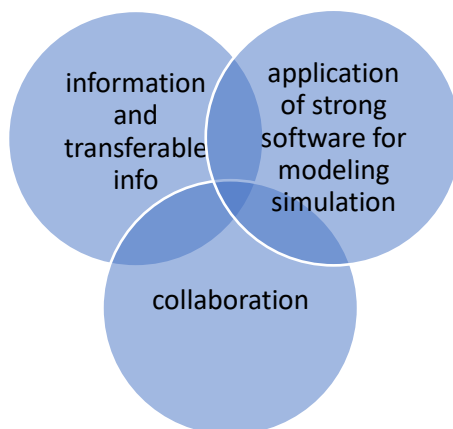


Figure 1, Elements of BIM (Course material)

When discussing sustainability, it is very easy to align it with green building. Sustainability covers a wide range of areas within the building industry and not only the environmental perspective, but also a social- and economical perspective. Therefore, a sustainable design is better than a green design (Krygiel & Nies, 2008). The developer might have a vision in mind when initiating a project, and as a sustainable building can be many things, the developer can choose to place the focus in one or more areas. This may be dependent on the economy or of the complaints value a sustainable construction has. But as far as possible, the developer should aim to satisfy all the areas of a sustainable design (Jrade & Jalaei, 2013). Sustainability is a lifecycle assessment, because making the most of a building requires an ongoing operation and maintenance (Zanni, et al., 2014). What makes it even more challenging (or maybe interesting) is that the concept of sustainability is still changing due to climate change and technology development.

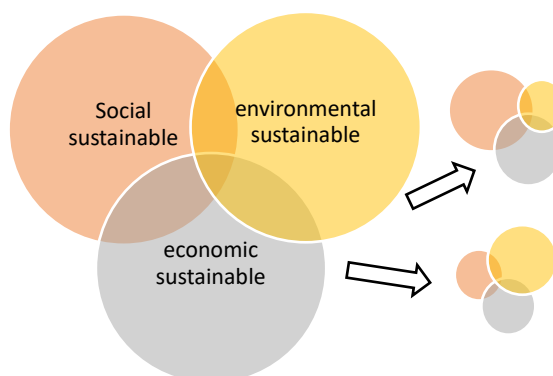
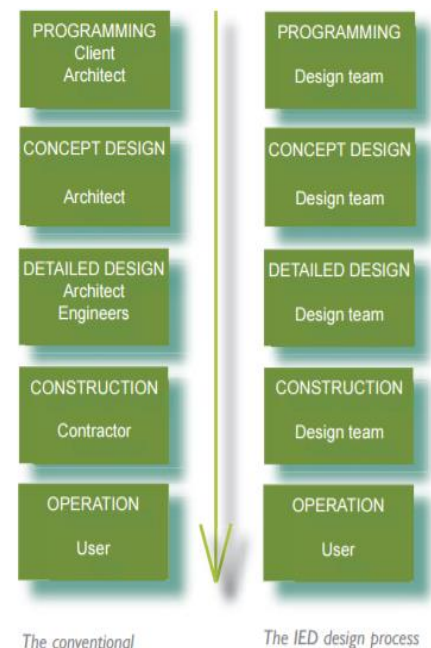


Figure 2, Elements of sustainable design

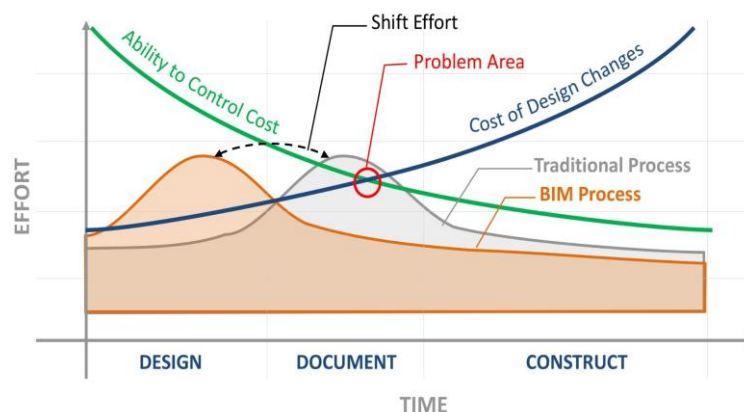
1.1 BIM and Sustainability

Buildings are becoming more and more complicated to complete, as the requirements increase and the industry develops. To be able to keep up, a strong method is to use BIM in cooperation with sustainable design. Using the methodology BIM, there are both pros and cons and therefore the challenge is to utilize BIM to the advantage of the project. BIM can advantageously be used to improve the buildings performance. This assignment will only see it from an energy and indoor perspective, but to achieve a sustainable design, it is necessary to take many more areas into account. BIM helps and promotes Integrated Energy Design (IED), which is a way of utilizing passive sustainability measures. IED needs to be done early in the design phase (Azhar, et al., 2009) because it is very sensitive to the placement of windows, shading and the building envelope and so on. This process must be implemented by a design team before all these elements are incorporated by an architect. A lot of changes can happen during a design process, and therefore BIM is essential in such a process.

A study on BIM for sustainable design has shown a slight increase in upfront cost of about 2-5 % but as result in life cycle savings of approximately 20-40 % on total construction cost (Azhar, et al., 2011). For a developer, an increase in the upfront cost can be straining but as seen from the study, sustainable designs are economically viable in the long run (energy, 2009). By using an integrated design team, it is possible to make different kinds of analysis' and tectonic design decisions before constructions starts. This enables changes without causing extra costs. By doing so, the process is moved to an earlier phase as seen in the graph below.



The conventional design process
 The IED design process
 Figure 3, The involved parties in the conventional- and IED design process, throughout the phases of a building (energy, 2009)



Graph 1, The effect of the traditional process and the BIM process (course material)

But to achieve a process as seen in the graph it is paramount that BIM and the right tools are implemented at the right time in the project. As stated earlier BIM should be implemented in the design phase, but the design phase can further be divided into smaller phases: conceptual design, schematic design and design development (Council, 2007).

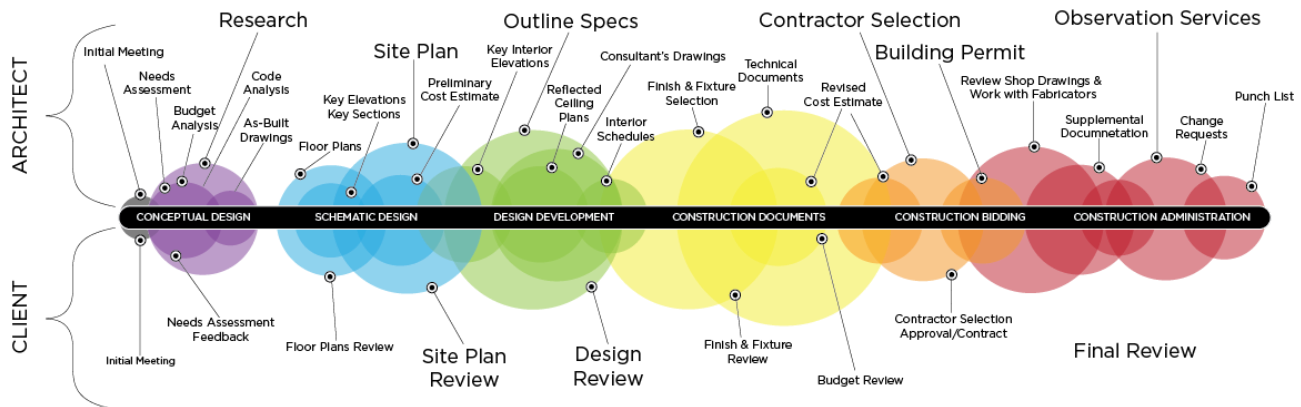


Figure 4, Different phases of developing a building and the related activities (Pinteterest Architecture)

So when in the design phase should energy and indoor climate analysis be performed? This is a very wide question and there is no one-sided answer. It very much depends on the needed analysis, but the designer should also be aware of how time-consuming and thereby expensive the simulations are. Doing time-consuming simulations very early in the design phase may be a waste of time and money, because few parameters have been set and are easily changed. Some analysis may also be done over several phases. E.g. the acoustical indoor climate depends on the geometry and material on the wall, which are two parameters that may be set in different phases of a design process.

BIM also brings along some cons, or should we say challenges: BIM requires that new measures are made. As in any sort of process, it is difficult to implement new procedures in an old process. Also being able to utilize BIM requires new types of competences that needs to be acquired by a lot of experience and education (Zanni, et al., 2014).

1.2 Indoor Environmental Performance

As there are many ways of conducting environmental performances, this assignment will focus on thermal comfort and moisture. These two topics are chosen because these two subjects are both important in the experience of the indoor climate and energy consumption and the perception and evaluation of both topics depend on each other.

Thermal comfort and moisture

Calculating the thermal comfort is a rather new method. The first comprehensive definition of thermal comfort for calculation was introduced in 1970 by the Danish professor Povl Ole Fanger. Before this, design was based on experience and notations. Thermal comfort is the condition of the mind that expresses satisfaction with the thermal environment. It consists of many parameters, which is roughly listed below (Alfano, et al., 2011):

- Metabolic rate
- Clothing insulation
- Air temperature
- Mean radiant temperature
- Air speed
- Relative humidity

When entering a room, one of the first thing you notice is often the temperature in the room and it is also a very common way to evaluate the indoor climate. Since a comfortable temperature is very individual, it is evaluated by an interval for mechanical cooled spaces. These criteria are set in DE/EN 15251 and is a way of categorizing and evaluating the indoor climate and it gives the developer something to aim for, by optimizing the indoor environment.

Table 1, The categories and the coherent room temperatures (DE/EN 15251)

Type of building or space	Category	Temperature range for heating, °C Clothing – 1,0 clo	Temperature range for cooling, °C Clothing – 0,5 clo
Offices and spaces with similar activity (single offices, open plan offices, conference rooms, auditorium, cafeteria, restaurant, class rooms) Sedentary activity – 1,2 met	I	21,0 – 23,0	23,5 – 25,5
	II	20,0-24,0	23,0 - 26,0
	III	19,0 -25,0	22,0 – 27,0

It is however necessary, when dimensioning after these criteria, to be aware of when the seasons changes and also clothing level. In relations to employees at offices and restaurants, there are often a requirement for their clothing, which will not change when the seasons change. These categories are set after the satisfaction of the thermal state of the body that is related to minimizing the percentage of dissatisfied and predicted mean vote from the ASHRE 7-point scale (see appendix).

Table 2, the categories and coherent Thermal state of the body (Alfano, et al., 2011)

The classification proposed by ISO 7730 [6] and EN 15251 [5] Standards.

Category		Thermal state of the body as a whole	
ISO 7730	EN 15251	Percentage of dissatisfied (PPD), %	Predicted mean vote (PMV)
A	I	<6	-0.20 < PMV < 0.20
B	II	<10	-0.50 < PMV < 0.50
C	III	<15	-0.70 < PMV < 0.70
–	IV	>15	PMV < -0.70 or PMV > 0.70

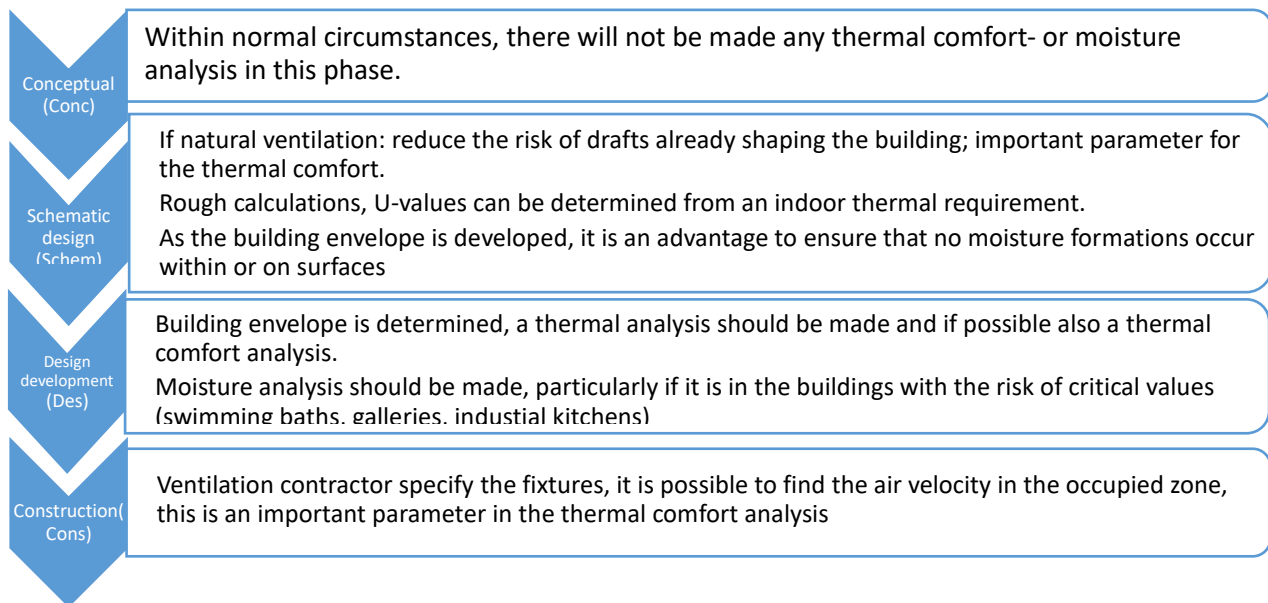
In terms of moisture, there are no specific design criteria. But investigating moisture in relation to indoor temperatures, there are two critical areas, that one needs to be aware of. For mostly older buildings, there may appear cold surfaces. This can result in, that the relative humidity exceeds 100% and condensation occurs on the surface. If this water is allowed to sit for an extended period, it may result in the emergence of mold formation (Ceylan, et al., 2013).

What may be more interesting is the way moisture can affect the perceived thermal comfort.

- High humidity → the room appear warmer. This is e.g. utilized at a swimming bath, where the clothing value is very low. By letting the humidity be high, it is not necessary to raise the indoor temperature. Discomfort by inhaling warm and moist air is due to inadequate cooling of the mucus membranes
- Low humidity → air appear less “heavy”. Humans prefer to inhale cool and dry air.

Air temperature and moisture are just two of the parameters that P. O. Fanger used to describe the indoor climate with the predicted mean vote and predicted percentage of dissatisfied. Even from Fangers Comfort model (Appendix) there will always be 5 % of a larger assembly that will be unsatisfied with the indoor thermal climate. But as an energy and indoor climate engineer one should always aim to satisfy as many people as possible. Since P. O. Fanger made his research, there has been made a great development within the technology for evaluating the thermal comfort and moisture. Following sections will explain how BIM can be used to evaluate the thermal comfort.

From this section, a schedule of the relevant evaluations within the different phases is made; this is also made to demonstrate in what phases the tools could be used. This is a continuation of Figure 4 with design phases. This should be seen as an explanation of the locations of the various tools in table 3 and 4, in the following section. The parentheses in the blue arrow is an abbreviation that will be used later in this report.



Data sharing

The analysis tools can either be integrated in the BIM software, in this case Revit, or it can be a stand-alone tool, where it is necessary to extract data into. This can be done by the different formats: e.g. IFC, gbXML, dwg or ecoXML. These formats contain different information and are therefore used according to the tool. The layout of the data is different and therefore requires that the tool that is used can read the format that is exported (Zanni, et al., 2014).

2. BIM FOR THERMAL COMFORT ANALYSIS

To make a reliable thermal comfort analysis, that can be used for dimensioning, it is necessary to have specific building element information (Laine, et al., 2007). Because of the information needed for these analysis, these tools will often first be used in the schematic design- or design development phase. The order of which these tools are used can also be reversed, so the programs are used earlier in the design phase to set the building information (U-values, etc.) to retain a certain thermal comfort.

The reliability and pros and cons for different tools will be listed below, to get an overview of the different possible tools available. The list is containing tools that is able to calculate different aspects of thermal comfort parameters, but also tools that can calculate the heating and cooling load of a building, since this is necessary to maintain the thermal comfort.

Table 3, Overview of thermal analysis tools, (Azhar, et al., 2009)

Tool (Phase)	Link to Revit	Thermal analysis	Ventilation Airflow	Heating/cooling	Pros	Cons
Ecotec (Schem/Des)	IFC gbXML dwg	X	X	X	<ul style="list-style-type: none"> Analysis results are stored in a single file Results are easily understood Quick and precise results 	<ul style="list-style-type: none"> Difficult user interface Long analysis run time Unstable program Inconsistent success of analysis
Integrated Environmental Solutions (Schem/Des)	IFC gbXML dwg	X	X	X	<ul style="list-style-type: none"> Direct Revit plug-in User interface mimics Revit Short analysis run time Large number of analysis 	<ul style="list-style-type: none"> Inconsistent analysis run success Limited model viewing capabilities

Green Building Studio (Schem/Des)	gbXML	X	<ul style="list-style-type: none"> Automated online process with step-by-step procedure Simple preparation work Automated gbXML error check Simple user interface 	<ul style="list-style-type: none"> Difficulties with larger files Unable to specify analysis types Difficulty linking gbXML data to online database 	
Insight 360 (Schem/Des)	Plug-in		X	<ul style="list-style-type: none"> Simple layout Easy to get started 	<ul style="list-style-type: none"> Some analysis has slow run-time
Heating and cooling loads (Schem/Des)	Int. tool	X		X	<ul style="list-style-type: none"> Easy to get started Not very visual Problems analyzing large buildings
CBE Thermal Comfort Tool (All phases)	No	X			<ul style="list-style-type: none"> Easy to get started Evaluate all parameters in a thermal comfort evaluation No building geometry is involved
Lindab (Des/Cons)	No		X		<ul style="list-style-type: none"> Very simple Fast calculations Easy to read results Limited room geometry Only products from Lindab

There are a lot of tools available, that is able to make evaluations within the thermal comfort area, but none of the tools that are investigated in this assignment can do a thermal comfort analysis with all the areas combined, which also assesses the building geometry. A lot of tools can do a thermal analysis in relation to the temperature, but not able to investigate how the temperature is perceived with a thermal comfort analysis. It would be particularly interesting to see how all the areas affect overall thermal comfort. This will be a major challenge, since many of the individual assessments are made in various design phases. Examination of the air velocity is e.g. often late in a design stage, as this is very dependent on the chosen fittings. In addition, it is also necessary to evaluate the items individually, in order to secure a construction of a high quality and finesse.

2.1 Thermal Comfort and Building requirements

According to the building requirements 6.2 PCS. 1 Analytical determination and interpretation of thermal comfort is done by calculating the PMV and PPD indices and local thermal comfort criteria. This evaluation can be done with the *CBE Thermal comfort tool*.

For non-residential buildings, the maximum number of hours per years during which an inside temperature of respectively 26 ° C and 27 ° C must not be exceeded, is established by the developer. For housing, a maximum of 100 hours per. year where the inside temperature exceeds 27 ° C is allowed, and 25 hours per year when the inside temperature exceeds 28 ° C. None of the above tools can do this evaluation.

According to the building requirements 6.3.1.1 PCS. 3; To avoid drafts, the air velocity in the occupied zone in rooms with sedentary activity may not exceed 0.15 m / s. The threshold depends on the activity, air temperature and air turbulence intensity. This evaluation can be done with the tools: Ecotec, IES, GBS and Lindab.

3. BIM FOR MOISTURE ANALYSIS

Moisture can be seen as a subtopic of thermal comfort. This topic is highlighted, since it is a more difficult topic to evaluate on its own. Indoor humidity depends on several factors, such as the air exchange, air flow, moisture sources and moisture exchange with materials.

When there is moisture diffusion through a building envelope, the water vapour might condensate within the envelope. It is therefore very important that the moisture balance through the envelope, can also include the moisture in liquid form. These different parameters all effect the energy, moisture and air balance.

Table 4, Overview of moisture analysis tools, (Woloszyn & Rode, 2008), (Michaelsen & Svendsen, 2011)

Tool (Phase)	Link to Revit	Relative humidity	Diffusion through envelope			Pros	Cons
			Vapor	Liquid	Moist air		
Insight 360 (Schem/Des)	Plug-in	X				Error! Reference source not found.	Error! Reference source not found.
Heating and cooling loads (Schem/Des)	Int. tool	X				Error! Reference source not found.	Error! Reference source not found.
BSim (Des)	No	X	X		X	<ul style="list-style-type: none"> • Many different analyses • Include large amount of information and user behavior 	<ul style="list-style-type: none"> • Limited graphic • Very time consuming
TRNSYS (Schem/Des/c on)	No	X	X	X		<ul style="list-style-type: none"> • Simple to use • Fast run-time • Lots of components 	<ul style="list-style-type: none"> • Often encounter error messages
IDA-ICE (Schem/Des)	No		X		X	<ul style="list-style-type: none"> • Large range of phenomena • Intuitive to use • Can calculate in multi-zones simultaneously 	<ul style="list-style-type: none"> • Slow run-time

What is quite interesting to see, is that only a few of the thermal analysis tools, that are also linked to Revit, includes moisture analysis, since it is a part of the overall thermal comfort. This is due to the fact that the tools are not well suited to predict moisture transfer processes in buildings. Some tools evaluate airborne moisture transport and the heat transfer in the air and in the envelope. But, generally these tools cannot calculate moisture exchange between the air and its adjacent porous walls. To be able to evaluate a whole building it is necessary to include various physical processes dealing with moisture, such as heat, air and moisture balances in the air and in all elements of the building (Woloszyn & Rode, 2008).

There are no building requirements for moisture evaluation.

4. SIMULATIONS

Two of the investigated tools have been used, to do a further investigation on their capabilities and compare the results. The simulations are made on the same building, which is made in connection with the teachings of this class. Both tools can extract many more results than shown in this assignment, but only the relevant result will be highlighted.

4.1 Heating and cooling - Revit

The implemented simulation tool Heating and Cooling is investigated. To start the simulation, it is necessary to divide the building into relevant spaces. At first the simulation was started with every room as a separate space. The simulation was not able to finish. Therefore, the model was simplified, so only the large office on the 5th floor is evaluated in this assignment. This leads to the results:

Table 5, Results from using Heating and Cooling

Parameter	Values
Cooling setpoint	23 °C
Heating setpoint	21 °C
Supply air temperature	12 °C
Relative humidity	46 %
Peak cooling load	102,15 W
Peak heating load	94,64 W
Mixed Air Dry-Bulb Temperature	26 °C
Cooling Coil Entering Dry-Bulb Temperature	26 °C
Cooling Coil Entering Wet-Bulb Temperature	18 °C
Cooling Coil Leaving Dry-Bulb Temperature	11 °C
Cooling Coil Leaving Wet-Bulb Temperature	11 °C

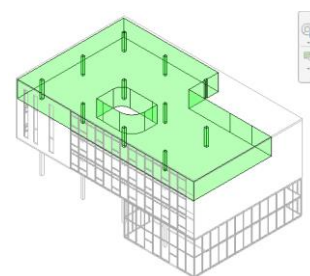


Figure 5, Evaluated area

4.2 Insight 360

The first step of doing an Insight simulation is to generate the Insight model. After a short time it is possible to access the results. The analysis was able to run on the entire building.

Table 6, Parameters from Insight 360,

Parameter	Value
Cooling set point	41,6 °C
Heating set point	36 °C
Relative humidity	46,33 %
Peak cooling load	3083,8 W
Peak heating load	2996 W

To get more usable and realistic results, it is necessary to change the set point of the model. It is also possible to visualize the heating and cooling load with Insight 360. This visualization will show the heating and cooling loads for individual building spaces.

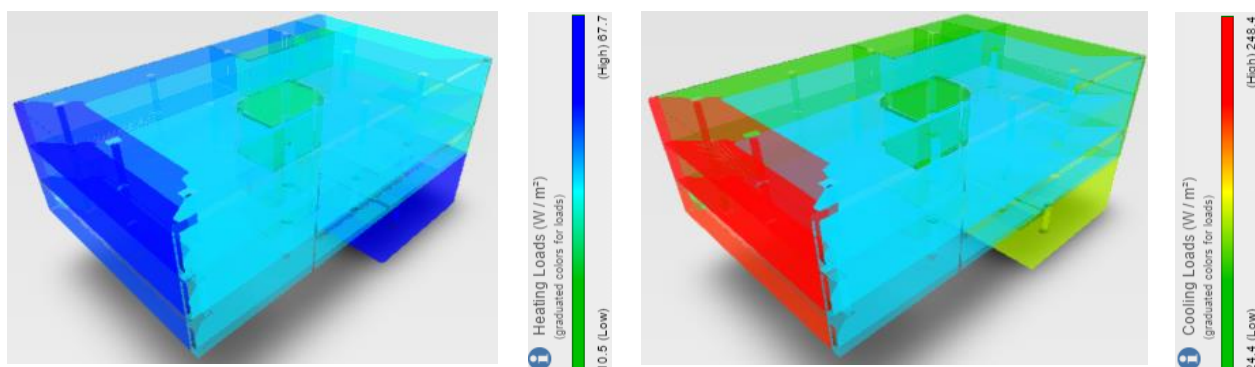


Figure 6, distribution of the heating and cooling load in the building

Using Heating and cooling will generate more useful and reliable results than Insight 360. Also the results from Insight 360 has given some questionable data. Heating and cooling did indicate some issues when simulating the entire building, but if a simpler building was used, it could have ensured that the simulations had a more equal basis.

These tools can be useful in a schematic design phase by optimizing the shape of the building to avoid problematic window areas that require large heating loads, and create cold areas that will create draft. However, it will be necessary to have some estimated values of the thermal properties of the building envelope. The pictures above are very useful for such an evaluation. Later, in the design phase, it is possible to optimize the

cooling- and heating load and secure acceptable temperatures, by optimizing on a room level to avoid overheating.

5. DISCUSSION

Often the codes behind the tools are not available, so it is not possible to know exactly how the program calculates. Therefore, it is also necessary to be critical towards the results to make them comparable to other calculation programs and when the indoor environment must be verified in relation to the Danish standards.

The gap between people and technology is the reason that BIM may not be used to its fullest of capabilities (Zanni, et al., 2014). If BIM is such a big advantage for the construction industry and sustainable design, we should make an extra effort to cooperate it in the training of professionals. This requires time and money, which often is the biggest bottle neck.

The gain of utilizing BIM, compared to when not using BIM, is really seen in the cooperation between the different profession involved. When people with different professional backgrounds meet and work together on the same building model, the bridge between them and the risk of error will decrease, as the understanding and available information increase. By optimizing the design process, it is possible to make energy analysis' earlier in the process, as seen in IED. The purpose of BIM is thus to create a process as seen in Graph 1, where it is possible to explore and make changes for the good of sustainable design, without having to compromise with the economy.

Optimizing the design process and BIM is not just using tools that have an automatic link between Revit and an evaluation tool. An equally important aspect is to promote a Revit model early in the design phase. If it is not available in the first place, it is not possible to perform the next step, which is indoor energy and indoor climate evaluations. Architects may start by using Sketch Up, which may delay the Revit model.

This assignment is based on academic literature, which has a varying age. Some of the literature is made within the last couple of years and some of it is about 10 years old. For an article, which refers to BIM and technology, the content quickly becomes outdated because of the rapid development, and therefore 10 years may be lot. The critique here is that the tools may already be updated or changed. It is therefore even more important to be critical about the literature in a study as this.

6. CONCLUSION

Building information modeling is a mythology that is being adopted in the construction industry, that can promote and assist sustainable design. In this assignment, sustainable design is only assessed from an energy and indoor climate view, but sustainable design is the ability to take divers areas into account, to improve and secure the environment and the future.

Thermal comfort analysis consists of many different parameters, but when analyses through BIM tools it is mostly only evaluated by the temperatures in the room. For the tools to include all the parameters, it will require many different balances, which will require more information, make it more complicated and will increase the run time. Povl Ole Fanger made a thermal comfort model, that contain all the parameters, but this has not yet been adopted by BIM tools. The next step could therefore be to develop a tool, that can make thermal comfort evaluation by also assessing the building geometry.

Moisture is one of the parameters that are used to evaluate the thermal comfort. From the investigation, there were not found many tools that can be linked to Revit, that also is able to evaluate moist transfer in a room or through the envelope. To make a thorough moisture evaluations it is therefore necessary to draw the building in BSim or one of the other suitable programs.

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APPENDIX

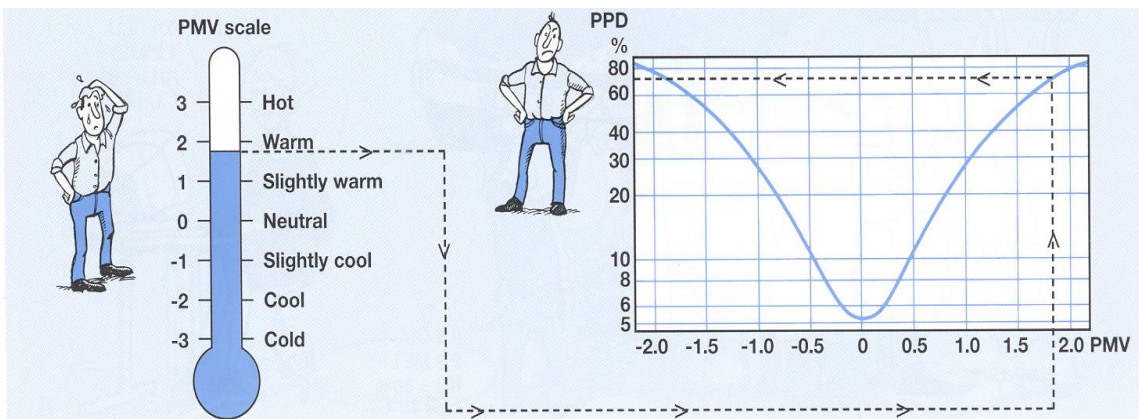
Fangers model of comfort

$$PMV = (0.303e^{-0.036M} + 0.028) \times [(M - W') - 3.05 \times 10^{-3} \cdot \{5733 - 6.99(M - W') - Pa\} - 0.42\{(M - W') - 58.15\} - 1.7 \times 10^{-5} \cdot M \cdot (5867 - Pa) - 0.0014 \cdot M \cdot (34 - Ta) - 3.96 \cdot 10^{-8} \cdot fcl \cdot (Tcl + 274)^4 - (Tr + 273)^4] - fcl \cdot hc \cdot (Tcl - Ta) \quad \dots(1)$$

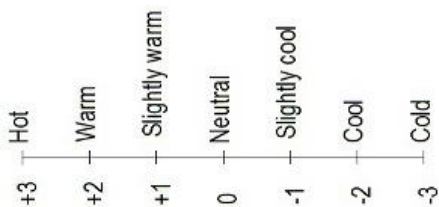
$$Tcl = Tsk - 0.155 \cdot Icl \cdot [3.96 \times 10^{-8} \cdot fcl \cdot (Tcl + 274)^4 - (Tr + 273)^4] + fcl \cdot hc \cdot (Tcl - Ta)$$

$$hc = \begin{cases} 2.38(Tcl - Ta)^{0.25} & \text{for } 2.38(Tcl - Ta)^{0.25} > 12.1\sqrt{Vair} \\ 12.1\sqrt{Vair} & \text{for } 2.38(Tcl - Ta)^{0.25} \leq 12.1\sqrt{Vair} \end{cases}$$

Tcl = clothing surface temperature
 Tsk = skin temperature
 Pa = RH Pa^*
 RH = humidity
 Pa^* = saturated water vapor pressure
 M = activity amount
 W' = work amount
 Ta = air temperature
 Tr = radiant temperature
 Icl = clothing thermal resistance
 $Vair$ = air velocity
 fcl = ratio, surface area of clothed body vs nude body



ASHRE 7-point scale



Poul Henning Kirkegaard, Aliakbar Kamari (Eds), Building information modeling (BIM) for Indoor Environmental Performance Analysis, 2017.