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Investigation of requirements for use of BIM-based LCA in early stages of building design

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Background

The building sector plays a big role globally as a consumer of energy and as an emitter of greenhouse gases. In the European Union, the building sector plays an even bigger role than it does globally. In the EU, the building sector consumes about 40% of the energy, and is responsible for 36% of the greenhouse gas emissions. It is therefore important to reduce impacts from buildings in the EU and other developed countries with similarly dominating building sectors.

Life cycle analysis (LCA) has recently become accepted as best-practice for measuring the impact of buildings over its life cycle, but its application to buildings is not yet very widespread. This is partly due to the laborious task of compiling a life cycle inventory. LCA can be used to find hot-spots for environmental impact in a product or building, and can therefore be used to improve the life cycle performance through one or several iterations. The work of compiling life cycle inventories can potentially be reduced by extracting material quantities and in-use energy consumption from building information models (BIMs). BIM is a shared digital representation of physical and functional characteristics of any built object which forms a reliable basis for decisions. The use of BIM has increased in recent years, and has e.g. already become a standard tool for several big building entrepreneurs in Norway as well as a requirement for public procurement projects in the United Kingdom.

Task description

There might be potential for improving the life cycle performance of buildings by using BIM-based LCA early in the design phase, and the student should identify the requirements for making meaningful use of such a methodology. To what degree are these requirements fulfilled today, and is it possible to fulfil them all?

Foreword

This master thesis concludes my master degree in industrial ecology at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology. The thesis is written during the spring of 2018 under the Department of Civil and Environmental Engineering, and counts as 30 ECTs.

Thanks to my supervisor Rolf André Bohne for the guidance and our meetings, as well as the idea for the topic. I would also like to thank Tobin Rist at Skanska for giving me some insight into industry context for the relationship between BIM and LCA.

Finally, I would like to express my gratitude to Ida Johanne, my friends, my family and my classmates for the continuous support and cheering throughout this master's degree. I could not have done it without you.

Anders Lilleheim Vik
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Summary

The building sector is currently facing several challenges related to sustainability. It is responsible for substantial contributions to e.g. climate change, waste production, energy consumption and land use change, at the same time as global population and building floor area per person is increasing. Our obligation towards the 2ºC target from the Paris Agreement and the United Nations Sustainable Development Goals for 2030 requires that effective measures for reducing the environmental impact from buildings in Norway and globally are implemented swiftly. One potential response is to improve best-practice for construction of buildings by optimizing the environmental performance over the entire life cycle.

The utilization of life cycle assessment (LCA) have become the standard method for measuring the environmental impact of buildings over their life cycle. This methodology may be used to compare the environmental impact of different solutions, and promote the more sustainable alternative.

This thesis investigates the application of LCA during the design stages of a building, to enable comparison of the sustainability performance of different design alternatives. The time demanding task of compiling life cycle data for such a LCA might be reduced significantly by extracting material quantities from virtual building models made with building information modeling (BIM). This thesis is a step towards identifying the requirements for meaningful use of such a methodology, as well as determining the feasibility of each requirement.

The results indicate that it is theoretically feasible to automate a whole-building LCA process by integrating environmental databases and LCA tools into BIM software. The technological maturity is probably not sufficient yet for such a symbiosis, but could be achievable if software developers are encouraged to develop more complex and interactive solutions. It is likely that this methodology can be applied to the early design phase of buildings, with or without automation, and guide building designers towards some reductions in life cycle impact. The potential environmental improvement potential from utilizing this method is limited to gains from choice of materials, quantity of materials and use phase emissions. The method can not be used to improve the sustainability of materials or energy production, nor improve user behaviour.

More research is needed to decide whether it is practically feasible to use BIM-based LCA during building design. The potential benefits from using this method compared to other methods should be quantified. They are expected to be low compared to best-practice in building sustainability, but it might give substantial gains for complex building projects or designer with limited knowledge about building sustainability. When the potential benefits are known, they must be weighed against the cost to determine whether the utilization of BIM-based LCA during early design phases is desirable.

Norwegian summary

Bygningssektoren star foran mange utfordringer knyttet til bærekraft. Den er ansvarlig for betydelige bidrag til blant annet klimaendringer, avfallsproduksjon, energibruk og endringer i landareal, samtidig som verdens befolkning øker og bygningsarealet brukt per person øker. Vår forpliktelse til togradersmålet fra Parisavtalen og bærekraftsmålene til FN for 2030 krever at det iverksettes effektive tiltak veldig snart for å redusere miljøpåvirkningen fra bygninger i Norge og internasjonalt. Et slikt tiltak er å forbedre beste praksis for bygninger ved å optimalisere miljøvennligheten over hele livssyklusen.

Livsløpsanalyse (LCA) har blitt standarden for hvordan miljøpåvirkningen til bygninger over livsløpet måles. Metoden kan brukes til å sammenligne miljøpåvirkningen av ulike løsninger, og dermed finne ut hvilket alternativ som er best med hensyn til miljøet.

Denne oppgaven ser på bruk av livsløpsanalyse i designprosessen for bygninger, som et verktøy for å sammenligne miljøpåvirkningen av ulike design Den tidkrevende prosessen med å samle en inventarliste for livsløpsanalyse kan reduseres betydelig ved å hente ut data om materialmengder fra virtuelle bygningsmodeller laget med bygningsinformasjonsmodellering (BIM). Denne oppgaven er et steg på veien mot å identifisere forutsetningene for fornuftig bruk av en slik metode, samt å finne ut om hver forutsetning er realiserbar.

Resultatene tyder på at det er teoretisk mulig å automatisere en bygnings-LCA ved å integrere database med miljøinformasjon og LCA-verktøy inn i BIM-programmer. Den teknologiske modenheten er sannsynligvis ikke tilstrekkelig for å få til en slik symbiose, men kan kanskje oppnås dersom programutviklere får insentiver til å utvikle mer komplekse og interaktive løsninger. Det er sannsynlig at denne metoden kan brukes tidlig i designfasen av bygninger, med eller uten automasjon, og dermed veilede bygningsdesignere mot lavere miljøpåvirkning. Potensialet for lavere miljøpåvirkning fra å bruke denne metoden er begrenset til forbedringer fra valg av materialer, materialmengder og utslipp fra bruksfasen. Metoden kan ikke brukes til å forbedre hvor bærekraftige materialene eller energiproduksjonen er, eller forbedre bruksmønstre.

Det trengs mer forskning for å finne ut om det er gjennomførbart å bruke BIM-basert LCA i bygningsdesign. De potensielle fordelene med denne metoden i forhold til andre metoder bør beregnes. De potensielle fordelene er antatt å være små sammenlignet med beste praksis for bygningsdesign, men de kan kanskje være av betydning ved komplekse bygningsprosjekter eller for designere med begrenset kunnskap om bærekraftige bygninger. Når forbedringspotensialet fra bruken av denne metoden er kjent, bør det vurderes om forbedringene er verdt kostnadene de medfører for å finne ut om bruk av BIM-basert LCA i designprosessen for bygninger er ønskelig.

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List of abbreviations

AIA	American Institute of Architects
AEC sector	Architecture, engineering and construction sector
BIM	Building information modeling
DBB	Design, bid and build
GHG	Green house gas
IDM	Information delivery manual. A manual that gives specific and relevant information in an IFC-file at a given time for a defined task (Bråthen, Flyen, Moland, Moum, & Skinnarland, 2016)
IFC	Industry foundation class. A neutral and open file format that enables exchange and integration of information between CAD programs and other software (Bråthen et al., 2016)
IFD	International framework for dictionaries. A dictionary with terms used in IFC-files, that are defined for several languages (Bråthen et al., 2016)
LCA	Life cycle assessment
LCI	Life cycle inventory
LOD	Level of development
LOI	Level of information
ISO	International standard organisation
SDG	Sustainable development goals
UN	United Nations

1 Introduction

1.1 Background

Buildings are one of the most basic and important infrastructures we have. This is reflected in how much time we spend inside them, the amount of money spent on buildings, and the huge quantities of resources we put into making and maintaining them. The building sector is the single largest consumer of energy and natural resources in the world, and is therefore a key sector in the worlds efforts towards increased sustainability (Nejat, Jomehzadeh, Taheri, Gohari, & Abd. Majid, 2015; Yeheyis, Hewage, Alam, Eskicioglu, & Sadiq, 2013). Buildings relate to several of the United Nations (UN) sustainable development goals (SDGs) for 2030 that were agreed upon in 2015 (United Nations, 2015). The UN SDGs that are most relevant for the building sector are shown in Figure 1, where buildings play a part as a consumer, indirect polluter and land occupier.

Figure 1: UN SDGs that are related to sustainability in buildings (United Nations, 2015).

Climate change, which is addressed in UN SDG number 13, is one of the biggest environmental challenges that human society face today. 197 parties agreed to limit global warming to 2°C above pre-industrial levels through the Paris agreement at the 22nd Conference of the Parties (COP22) in 2015, which demands drastic and worldwide reductions in greenhouse gas (GHG) emissions to the atmosphere (UNFCCC, 2018). The goal to mitigate global warming and the corresponding climate change is also rooted in the UN SDGs, which include specific targets to be met by 2030 (United Nations, 2015). A study suggest that the chances of achieving the two degree target are only 5%, and that the chance of success will decrease further as time passes without stronger mitigation efforts (Raftery, Zimmer, Frierson, Startz, & Liu, 2017). With the given circumstances, all sectors must strive towards reductions in GHG emissions (IPCC, 2014).

Buildings were responsible for 18.4% of the global GHG emissions in 2010, and should be decarbonized and made more energy efficient in response to the threat of climate change (IPCC, 2014). The energy consumed per area for residential and non-residential buildings has decreased substantially from 1990 to 2014, but the energy consumption in the building sector still increased by 35% in the same period due to bigger growth in building floor area (Global Alliance for Buildings and Construction, 2016; IEA, 2016). At present, the global population and its purchasing power is still increasing at the same time as an increasing amount of people move to cities, with the implication that an increase of 50% to the global building floor area is expected by 2050 according to current trends (Global Alliance for Buildings and Construction, 2016). The abovementioned factors imply that the sector faces major challenges with reducing its GHG emissions, and should therefore be subject to thorough investigation.

A global status report made in preparation for COP22 presents seven important measures that the building sector should implement in their efforts towards lower GHG emissions, including measures from renovation to decarbonization of energy (Global Alliance for Buildings and Construction, 2016). All these measures could be addressed through a life-cycle approach based on life cycle assessment (LCA), which can be used to evaluate, compare and (in theory) optimize building designs with respect to GHG emissions and other environmental impact categories. LCA is however a labour-intensive process, largely because a lot of data gathering is required to map the material and emission flows throughout the life cycle of a product.

A concept that has received increasing interest over the last years is an integration of LCA into building information modelling (BIM), which can simplify the data gathering process for the LCI. BIM is a collaboration methodology used in the architecture, engineering and construction (AEC) sector, where drawings and information is shared via a virtual model. A symbiosis of BIM and LCA can take advantage of material information from BIM models to ease (and possibly automate) the data gathering process for LCAs (Meex, Hollberg, Knapen, Hildebrand, & Verbeeck, 2018; Rist, 2011; Röck, Hollberg, Habert, & Passer, 2018; Soust-Verdaguer, Llatas, & García-Martínez, 2017) Such a symbiosis might be a powerful tool to further improve building designs, and could address several of the sustainability measures presented by the COP22 global status report (Global Alliance for Buildings and Construction, 2016). The use of BIM-based LCA early in the design phase for buildings has received significant interest in the research literature in recent years, and should be investigated further.

The use of BIM has increased over the last decade, and the methodology has become relatively widespread in the AEC industry. The potential benefits from using BIM-based LCA in the design phase in buildings, the continuous development of BIM software and the increased BIM adaptation in industry substantiates the need to look closer at the possibilities and challenges with BIM-based LCA.

Software that attempts to fulfil the role as a BIM-enabled LCA tool exist already, and these concepts will be presented in this thesis with their corresponding features. Current research on BIM-enabled LCA is mostly limited to manual and semi-automatic solutions, and has yet to describe or investigate all the aspects of automated BIM-enabled LCA used for documentation purposes or early design phase optimization.

1.2 Purpose and objectives

The main purpose of this thesis is to investigate what features a methodology for BIM-enabled LCA in the early design phase for buildings would need in order to give a sufficient representation of the life cycle emissions from a building, and to find out how and if such a method can be useful for reducing life cycle GHG emissions of new or existing buildings. This main purpose will be achieved by answering the following research questions:

1. What are the requirements for making use of BIM-based LCA during early design stages for a building?
2. To what degree are these requirements fulfilled today, and is it possible to fulfil them all?
3. How viable is it for the AEC industry to use such a methodology to increase building sustainability?

1.3 Scope and limitations

Buildings can become more sustainable through other measures than building design, but several of these aspects, such as user behaviour and energy/electricity production, will not be covered in this thesis.

This thesis does not attempt to quantify the potential emission savings from using BIM-based LCA during early design phase.

BIM-based LCA might be used for several types of construction objects, such as roads and bridges, but this thesis is limited to buildings. This is because buildings differ in e.g. lifetime and use phase complexity from other built objects, and therefore have unique methodological considerations.

1.4 Structure of the thesis

The thesis consists of two main parts. The first part presents existing research, methodologies and standards, as well as the methods used in the thesis work. Part two presents the deductions that can be made from the background theory, and a discussion of these results. The thesis contains no experimental data, and is purely a gathering of existing information that is combined, analysed and put into a context that is not yet fully explored in existing research.

2 Theory

2.1 Sustainability in the building sector

The building sector is the biggest consumer of resources globally, and is responsible for 40% of energy use, 12% of water use, 30% of raw material use and 12% of land use (Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013; UN Environment, 2015). Energy is in this case considered a resource, of which buildings consume approximately 40% of the annual global energy consumption (Nejat et al., 2015). Through these 40 % of energy consumption, buildings are responsible for emitting 12% of the global annual GHG emissions, as can be seen in Figure 2. The figure also shows that buildings have additional emissions amounting to 6.4%, giving a total share of the global annual GHG emissions of 18.4%. The building sector is also responsible for nearly 40% of waste generation (UN Environment, 2015).

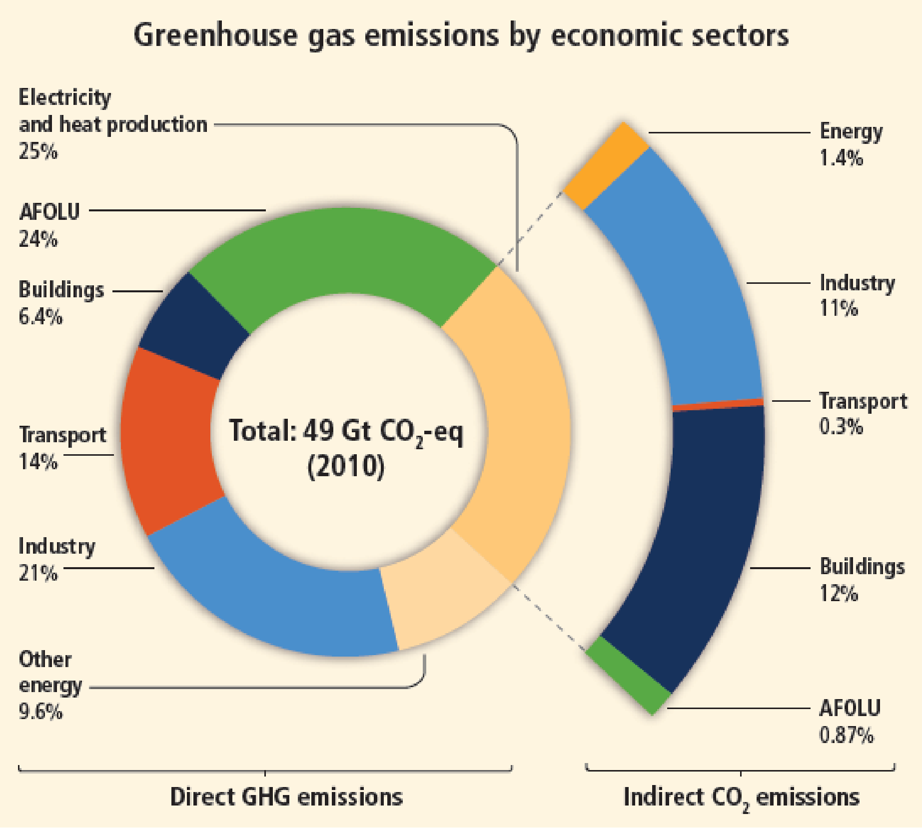
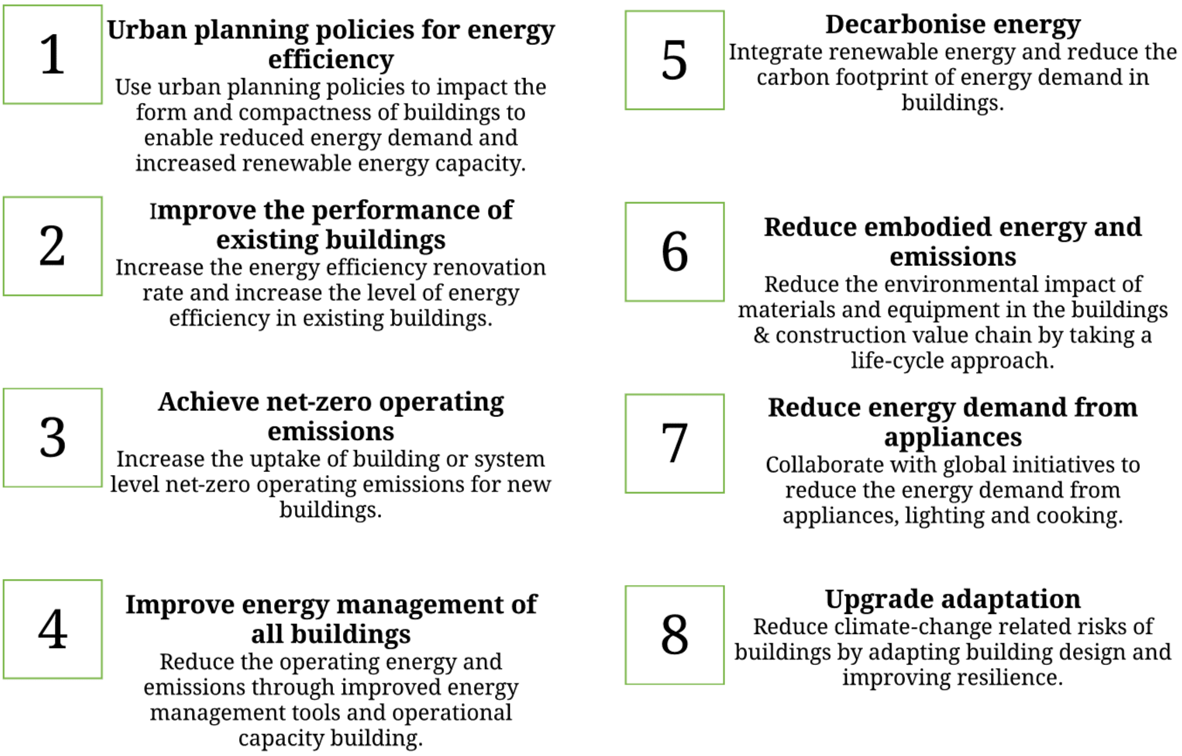


Figure 2: Global GHG emissions in 2010, divided by five economic sectors. (IPCC, 2014)

In the European Union, the building sector plays an even bigger role than it does globally. In the EU, the building sector consumes about the same share of energy, 40%, but buildings are responsible for a much bigger share of GHG emissions, namely 36% (European Commission, 2018a). The construction sector use about 50% of the raw materials processed in Europe, and is responsible for about approximately 30% of European waste generation (Herczeg et al., 2014). It is therefore important to reduce impacts from buildings in the EU and other developed countries with similarly dominating building sectors. Establishing good standards for sustainable buildings in developed countries would also help developing countries avoid similarly high emissions from new buildings in their future building stock. Developing countries have emerging and new construction markets that will be much harder to make sustainable once they have been built compared to making sustainable buildings in the first place in this window of opportunity (Global Alliance for Buildings and Construction, 2016).

In preparation to COP22, France had a report made called "Towards zero-emission efficient and resilient buildings - GLOBAL STATUS REPORT 2016" (Global Alliance for Buildings and Construction, 2016). This report presents and ranks eight strategies that the authors find are important to reduce climate impact from the building sector. The strategies are presented in Figure 3.



1 **Urban planning policies for energy efficiency**
Use urban planning policies to impact the form and compactness of buildings to enable reduced energy demand and increased renewable energy capacity.

2 **Improve the performance of existing buildings**
Increase the energy efficiency renovation rate and increase the level of energy efficiency in existing buildings.

3 **Achieve net-zero operating emissions**
Increase the uptake of building or system level net-zero operating emissions for new buildings.

4 **Improve energy management of all buildings**
Reduce the operating energy and emissions through improved energy management tools and operational capacity building.

5 **Decarbonise energy**
Integrate renewable energy and reduce the carbon footprint of energy demand in buildings.

6 **Reduce embodied energy and emissions**
Reduce the environmental impact of materials and equipment in the buildings & construction value chain by taking a life-cycle approach.

7 **Reduce energy demand from appliances**
Collaborate with global initiatives to reduce the energy demand from appliances, lighting and cooking.

8 **Upgrade adaptation**
Reduce climate-change related risks of buildings by adapting building design and improving resilience.

Figure 3: Key strategies for reducing climate change impact from building and construction. Modification of figure from (Global Alliance for Buildings and Construction, 2016).

The building sector continually improves building sustainability. The building sector is pressured towards more sustainable solutions through e.g. standards, government pressure and economic benefits from achieving sustainability or energy use certification. Several certification schemes exist for building sustainability, such as BREEAM and LEED, which currently have heavy focus on GHG emissions. So-called 2nd generation building certification systems have also begun to emerge, which use multi-criteria optimization (Kreiner, Passer, & Wallbaum, 2015). Major improvements for use phase energy consumption have been achieved over the past couple of decades. Current efforts to improve sustainability guidelines include optimization of use phase emissions and embodied emissions (Ibn-Mohammed et al., 2013). Danish building standards for 2020 are actually close to being optimized in terms of embodied emissions from insulation versus use phase emissions from heating, due to the future improvements in sustainable electricity and energy (Sohn, Kalbar, & Birkved, 2017).

2.2 BIM

Building information modelling (BIM) is defined by ISO 29481 from 2016 as “use of a shared digital representation of a built object (including buildings, bridges, roads, process plants, etc.) to facilitate design, construction and operation processes to form a reliable basis for decisions” (ISO, 2016a). BIM has also been used as an abbreviation for “building information model” in the literature, meaning that it can represent both a model and the process of modelling (BIMForum, 2017a; Volk, Stengel, & Schultmann, 2014). BIM is a large topic that is covered extensively in several books (Barnes & Davies, 2014; Eastman, Teicholz, Sacks, & Liston., 2008; Hardin & McCool, 2015; Kubba, 2012; Mordue, Swaddle, & Philp, 2016; Shepherd, 2016; Weygant, 2011), and so this chapter will be limited to briefly explaining what BIM is, what the benefits of using BIM are, BIM adaptation in the industry, BIM standards and level of development (LOD) for a BIM.

2.2.1 What is BIM?

When the first three-dimensional models with additional embedded information began replacing traditional two-dimensional drawings in 1985, the term “object based 3D models” was introduced to distinguish them from each other (Bråthen et al., 2016). The term BIM became the common term instead of “object based 3D models” later on, in the 1990s (Kubba, 2012). Since then BIM has evolved to become a collaboration methodology where stakeholders plan, design, interact and communicate throughout the building’s life cycle, from the design phase to the demolition phase, and use tools such as e.g. collision control, sequencing, simulations and parameterized optimization (Barnes & Davies, 2014; Hardin & McCool, 2015). Even so, the use of BIM is not very mature yet, and many of the potential benefits from BIM are yet to be realised (Barnes & Davies, 2014; Eastman et al., 2008; Hardin & McCool, 2015; Kubba, 2012). The idealized use of BIM is to use it throughout the life cycle of the building in question, but it can also be used for a few selected stages such as in the design of mechanical service systems (Barnes & Davies, 2014).

Simply put, BIM can be seen as a virtual 3D CAD model with object specifications (Weygant, 2011). This could be a virtual model stored in the cloud with live updating where stakeholders can work simultaneously, or the adjoining of several models made by separate stakeholders into one common model. There are several ways to configure how stakeholders interact with BIM, and should be explained in the context of a construction procurement process. There are however several types of procurement processes, with several variations of each and varying practices between countries that evolve over time (Barnes & Davies, 2014; Eastman et al., 2008). One example of a traditional procurement process for construction will be presented in the following paragraph, to give an example of how the information flow in the procurement process can change with the introduction of a BIM platform or a BIM manager.

In the design, bid and build (DBB) procurement method, the information flow is not managed by a single stakeholder or platform, but rather through a chain of stakeholders. Figure 4 shows an example of a DBB process where information flows between e.g. the structural designer and the architect, from the architect to the contractor, from the contractor to the sub-contractors, and finally from the sub-contractors to the sub-sub contractors. The figure also shows the same process and stakeholders with the addition of a BIM manager, where information flow is compiled and exchanged centrally through BIM, and further exchanged directly to contractor, sub-contractor etc. More examples of procurement methods with and without a BIM manager can be found in several books about BIM (Barnes & Davies, 2014).

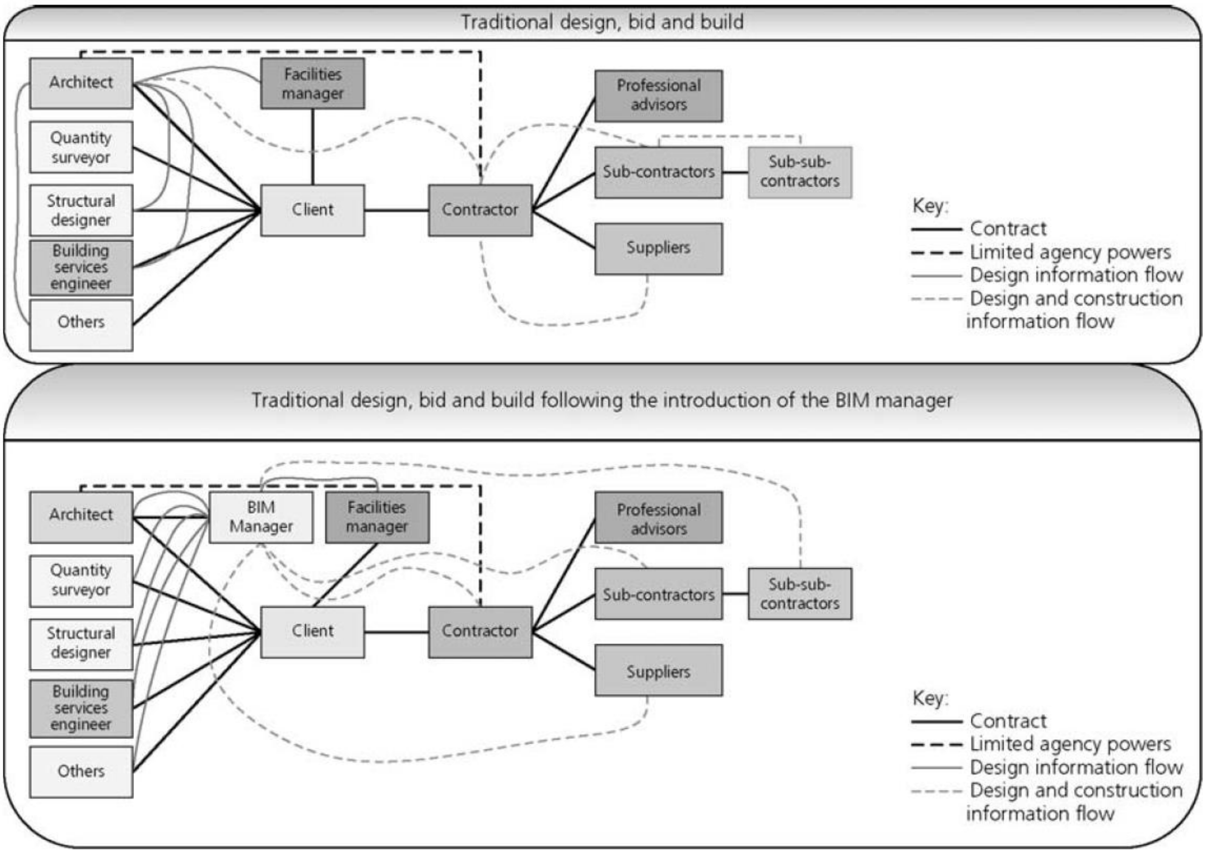


Figure 4: Stakeholders involved in "design, bid and build" procurement of a building, with roles and information flow without and with BIM application (Barnes & Davies, 2014).

2.2.2 Level of development (LOD)

Virtual models can be made with varying levels of development. Level of development include requirements for level of detail and level of information in model elements (Mordue et al., 2016). Level of detail refers to how much graphical details the model element/object has, and level of information refers to all kinds of information except graphical details (Mordue et al., 2016). Information can in this context mean e.g. material density, permeability properties, cost, colour, function, power requirements or coating for a model element.

To make sure that misunderstandings and confusion between owners, designers, engineers etc. are avoided, several parties have made definitions for different levels of development for model elements in BIMs. By referring to these definitions, all parties involved know approximately how developed the virtual model they are collaborating on should be. Norway have currently no national standard for LOD classification. The American Institute of Architects (AIA) define the different levels of development in the document E203 as "the minimum dimensional, spatial, quantitative, qualitative and other data included in a Model

Element to support the Authorized Use associated with such LOD" (The American Institute of Architects, 2013a). The AIA presents six LOD levels that progress from conceptual to specific details and information. These are shown in Table 1, together with interpretation and examples made by BIM Forum.

Table 1: Definition of each level of development (LOD) by The American Institute of Architects (AIA), with corresponding interpretation and example by BIMforum below.

[1] (The American Institute of Architects, 2013b)

[2] (BIMForum, 2017a)

[3] (BIMForum, 2017b)

LOD100	"The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.".[1] BIMForum Interpretation: "LOD 100 elements are not geometric representations. Examples are information attached to other model elements or symbols showing the existence of a component but not its shape, size, or precise location. Any information derived from LOD 100 elements must be considered approximate".[2] Example: "cost/sf attached to floor slabs".[3]
LOD200	"The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.".[1] BIMForum interpretation: "At this LOD elements are generic placeholders. They may be recognizable as the components they represent, or they may be volumes for space reservation. Any information derived from LOD 200 elements must be considered approximate".[2] Example: "light fixture, generic/approximate size/shape/location".[3]
LOD300	"The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.".[1] BIMForum interpretation: "The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs. The project origin is defined and the element is located accurately with respect to the project origin".[2] Example: "Design specified 2x4 troffer, specific size/shape/location".[3]
LOD350	"The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element.".[1]

	BIMForum interpretation: “Parts necessary for coordination of the element with nearby or attached elements are modeled. These parts will include such items as supports and connections. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs”.[2] Example: “Actual model, Lightolier DPA2G12LS232, specific size/shape/location”.[3]
LOD400	"The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.".[1] BIMForum interpretation: “An LOD 400 element is modeled at sufficient detail and accuracy for fabrication of the represented component. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs”.[2] Example: “As 350, plus special mounting details, as in a decorative soffit”.[3]
LOD500	"The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements.".[1] BIMForum interpretation: “Since LOD 500 relates to field verification and is not an indication of progression to a higher level of model element geometry or non-graphic information, this Specification does not define or illustrate it.”.[2] Example: As LOD400.[3]

An example of a massing study done at LOD 100 is given in Figure 5 together with the completed project. Examples of a window at increasing level of development is shown in Figure 6. These figures give only an impression of the level of detail, not the level of information.

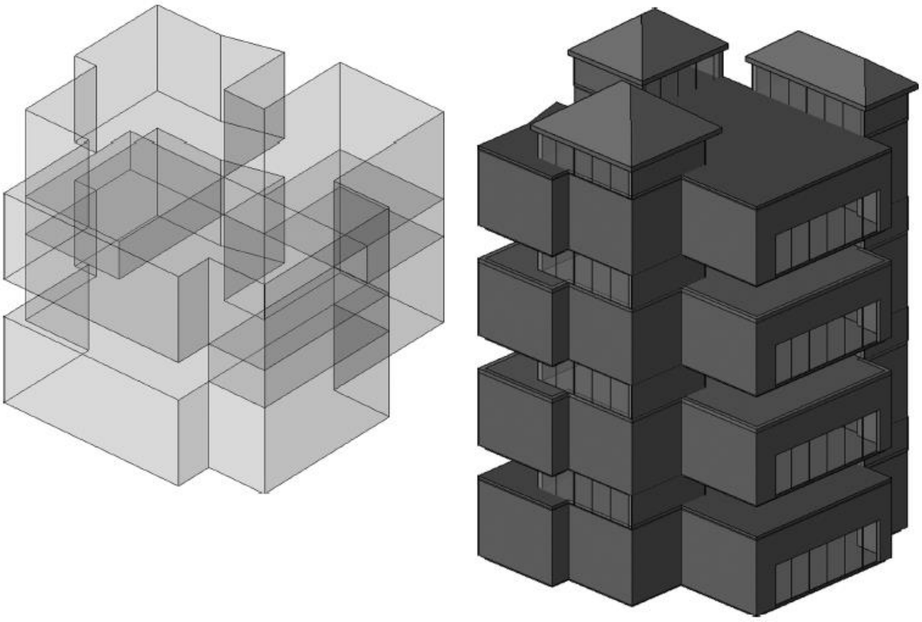


Figure 5: An example of a massing study at LOD100 to the left, and the completed project to the right (Weygant, 2011).

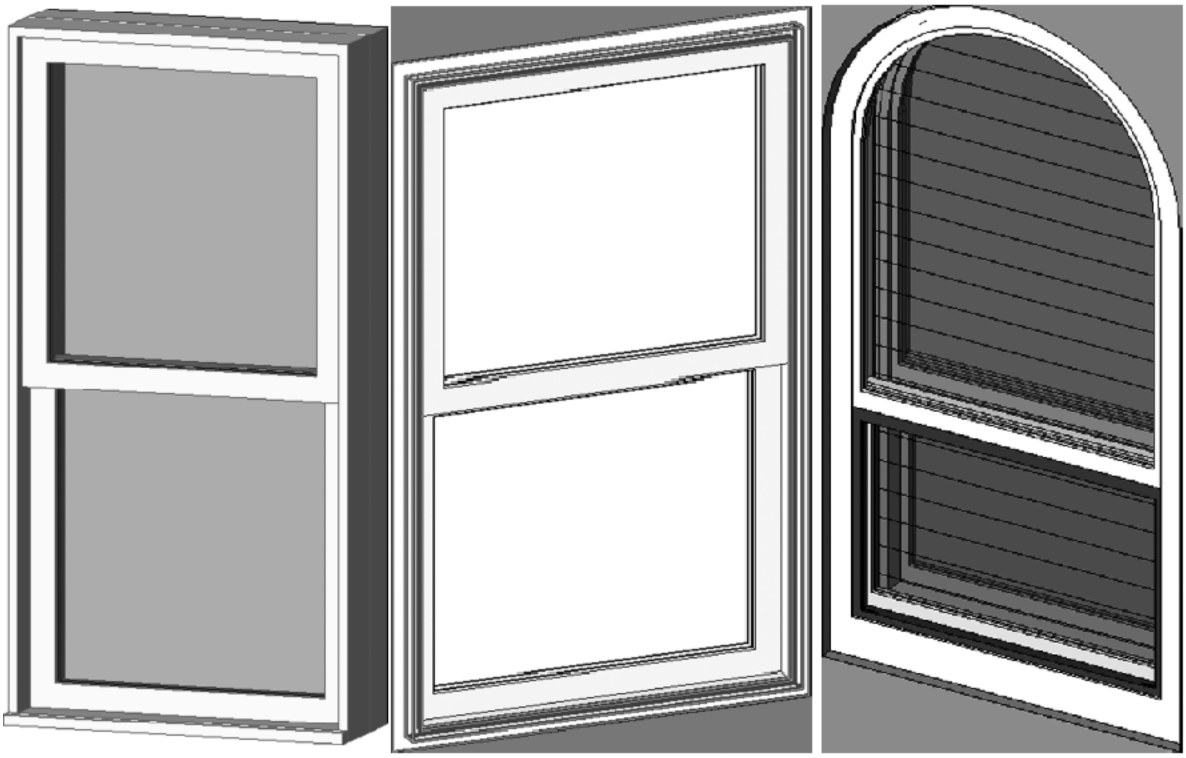


Figure 6: Example representations of LOD200, LOD300 and LOD400 according to AIA standards (Weygant, 2011).

The LOD system presented by AIA is a formal classification system, and in practice there are several steps between the defined levels of development presented above. In fact, the AIA state that it is not possible to describe a BIM model under development by one specific LOD definition, because different design development "packages" are at different levels of development at a given time (Hardin & McCool, 2015). As can be seen from an example design timeline in Figure 7, the different design development "packages" are at or in between LOD levels after the conceptual stage until the project is finished. The level of development evolves with time, and some of the packages are dependent on others.

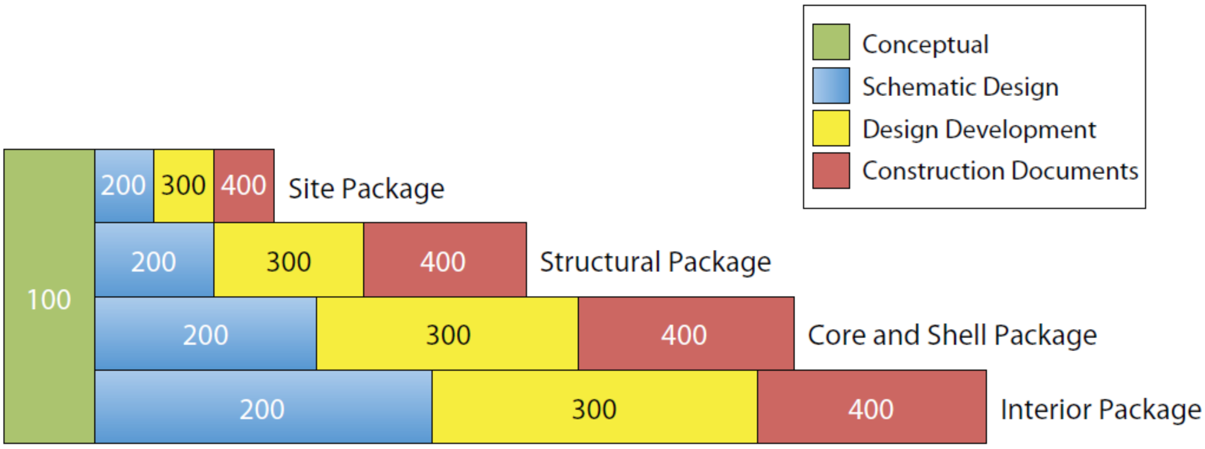


Figure 7: An example of a design schedule with four design stages with corresponding LOD requirements (Hardin & McCool, 2015).

The LOD definitions presented above are the ones used in the United States of America, which also dominate in academic research papers, but other LOD systems also exist. The United Kingdom has another system with BIM definitions referred to as BIM maturity levels, which range from level 0 to level 3 (Barnes & Davies, 2014; Shepherd, 2016).

2.2.3 Benefits and challenges with BIM

The literature presents numerous potential benefits and challenges from implementing BIM in AEC projects. They are too many to be presented in detail in this thesis. Brief explanations are given for some essential arguments in the following two sub chapters.

2.2.3.1 Benefits

Many of the major advantages with implementing BIM are unlocked due to the increase in available information earlier in the design phase, as well as the quality of available information (Eastman et al., 2008). This enables earlier cost estimation and visualization, and enables the owner to assess feasibility and risk (Eastman et al., 2008; Kubba, 2012). BIM can also reduce net costs and risk for designers, contractors, owners and subcontractors (Kubba, 2012). The use of BIM shifts the design towards earlier project phases, and therefore enables design changes at lower cost and more control over cost, design and functionality (Hardin & McCool, 2015). This relationship is shown conceptually in Figure 8. Barnes and Davies argue that the greatest potential benefits from utilizing BIM come from integrated data sharing (Barnes & Davies, 2014).

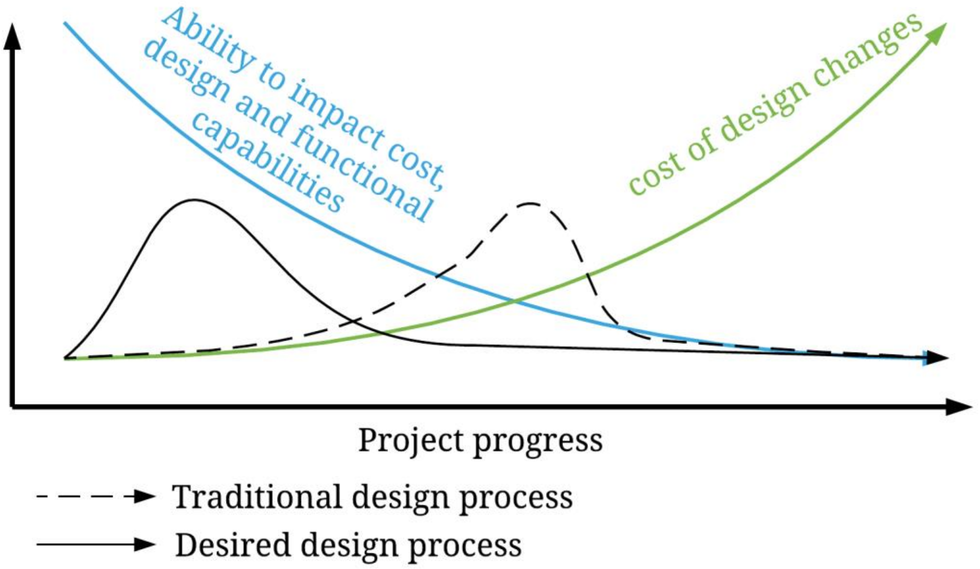


Figure 8: MacLeamy Curve that explains the relationship between cost of design changes and the ability to impact cost, design and functional capabilities as a project progresses. With BIM, more information is available early in the project process. Based on design from Hardin & McCool (Hardin & McCool, 2015).

Other important benefits from implementing BIM include identification of errors with clash detection, options for parametric modeling, enhanced facility management, enhanced collaboration, improved coordination, easier data sharing and quicker documentation production (Ghaffarianhoseini et al., 2017).

2.2.3.2 Challenges

Lack of demand for BIM, high costs and poor software interoperability are the main explanations from companies that don’t implement BIM (Ghaffarianhoseini et al., 2017). Especially smaller companies are at risk of having trouble with getting sufficient return on investment, partly because of low engagement in projects with BIM and little experience with BIM among the staff (Ghaffarianhoseini et al., 2017).

The transition to BIM introduces new and unknown elements for many companies, ranging from legal changes related to intellectual property to risk of potential errors when exchanging models between tools without use of IFC (Eastman et al., 2008; Ghaffarianhoseini et al., 2017). There is also risk of reduced understanding of responsibilities and obligations for participants, due to new work processes and methods for collaboration (Eastman et al., 2008; Ghaffarianhoseini et al., 2017; Kubba, 2012). Other potential challenges include cyber security, time- and cost investment during BIM adaptation as well as risk of complications and low data accuracy due to use of varying design practices and libraries in BIM models (Ghaffarianhoseini et al., 2017).

2.2.4 BIM adaptation

The use of BIM is becoming more and more widespread globally (Hardin & McCool, 2015). The adaptation of BIM (in all and any forms) in North America grew from 28% to 71% from 2007 to 2012 among engineers, architects, contractors and owners (McGraw Hill Construction, 2012). A survey from 2016 for the United Kingdom showed that 54% of the responding AEC constructors are aware of and using BIM in at least some of their projects (National Building Specification, 2016). 86% of the respondents from the same survey expected to be using BIM by 2017, which shows the speed of recent increase in BIM adaptation.

In Norway, the public sector administration company Statsbygg has used BIM (to at least some extent) for all projects since 2010 (Geospatialworld, 2017). However, Statsbygg expressed that the adaptation of BIM in projects (in general) is rather modest, and that it is often used as an additional tool in traditional project management instead of as a project management methodology (Bråthen et al., 2016). According to the main report from the project SamBIM (with collaborators like Fafo, NTNU, SINTEF, Skanska, Multiconsult, Statsbygg and Link Arkitektur) from 2016, the Norwegian building industry is currently transforming it’s view on digitalization, with a resulting increase in use of BIM (Bråthen et al., 2016). It can in general be summarized that the adaptation of BIM is increasing, both worldwide and in Norway, with bigger companies dominating as early adopters (Barnes & Davies, 2014). For instance, the Norwegian section of the project development and construction group Skanska currently have a BIM department and use BIM in all their projects (Rist, 2018). Some believe that BIM will become standard even for smaller companies in a few years time, in the same way that CAD was first believed to only be suitable for large companies when it still was a new technology, only to later become standard for large and smaller companies alike (Barnes & Davies, 2014).

2.2.5 BIM standards

Countries currently have varying level of standardization for BIM. There is a lot of ongoing development of guidelines and standards, as BIM methodology is constantly maturing and developing. Some international standards for BIM exist through the International Standard Organization (ISO), but these do not cover all areas of BIM practice and so several countries have established or are currently developing standards for BIM. The EU currently refer to six BIM standards from the ISO as representative for the EU BIM standards (European Commission, 2018b; European Committee for Standardization, 2018a):

- ISO 12006-2:2015 - Building construction - Organization of information about construction works -- Part 2: Framework for classification
- ISO 12006-3:2007 - Building construction - Organization of information about construction works -- Part 3: Framework for object-oriented information
- ISO/TS 12911:2012 - Framework for building information modelling (BIM) guidance
- ISO 16739:2013 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries
- ISO 29481-1:2017 - Building information models - Information delivery manual - Part 1: Methodology and format
- ISO 29481-2:2016 - Building information models - Information delivery manual - Part 2: Interaction framework

ISO/TS 12911:2012 contains a framework that is meant to assist the development of international-, national-, project- or facility-level BIM guidance documents, which means that the international community have at least agreed on a generic framework for BIM practice, if not an all encompassing and specific standard (ISO, 2016b). Furthermore, ISO is currently developing several standards related to BIM, and so the standardization on the international level can be expected to increase in the near future. ISO standards related to BIM that are currently under development include:

- ISO/AWI 23386 - Building information modelling and other digital processes used in construction -- Methodology to describe, author and maintain properties in interconnected dictionaries
- ISO/DIS 19650 - Organization of information about construction works -- Information management using building information modelling
- ISO/NP 22057 - Enabling use of Environmental Product Declarations (EPD) at construction works level using building information modelling (BIM)

Several other BIM related ISO standards are also under development in collaboration with the European standardization committee CEN/TC 442 and others, and some standards are currently awaiting approval (European Committee for Standardization, 2018b; Standard Norge, 2018).

In parallel with the development of new ISO standards, the European Union have recently developed and published a handbook through the EU BIM Task Group that contains guidelines for how BIM should be introduced and used in public strategies and public procurement (EU BIM Task Group, 2018). Increasing the use of BIM is a deliberate policy in the EU, for both the public and private construction sector (EU BIM Task Group, 2017). The EU's vision is to build an "open digital construction market that sets the global standards", which calls for use of the open IFC format (EU BIM Task Group, 2017).

BuildingSMART is a big player in the development of BIM standards, which is an international organization that develop open BIM standards. The goal with open BIM is to make standards for BIM processes, workflows and procedures that are open source and available for everyone (BuildingSMART, 2018). The organization collaborates on standard development with several other international and national organizations, and have for example made the IFC standard that was adopted by ISO called ISO16739. BuildingSMART is also organized in several national departments, and they have departments in Norway and 17 other countries (BuildingSMART Norge, 2018). Figure 9 illustrates BuildingSMART's vision of how BIM ties all the disciplines together, with the use of IFC, IFD (International framework for dictionaries) and IDM (Information delivery manual) standards.

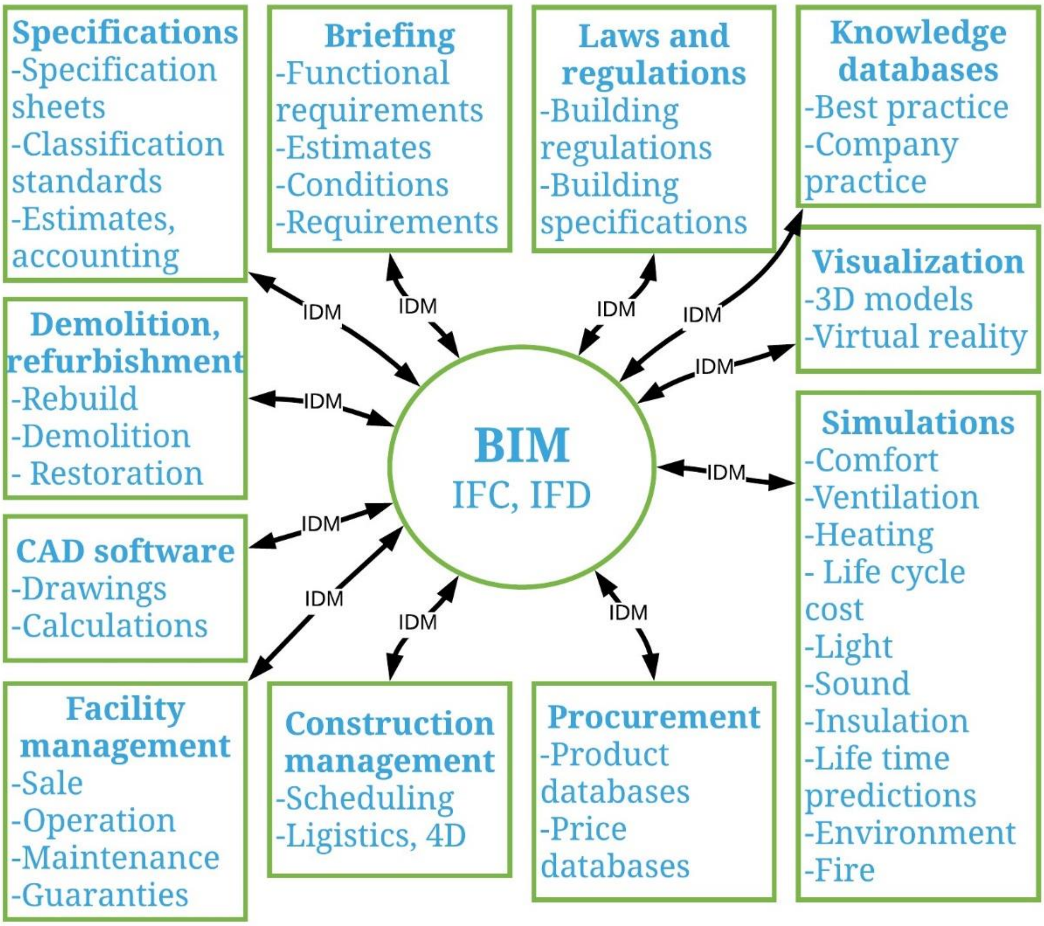


Figure 9: Vision by BuildingSMART for discipline interaction with BIM. Modification of figure from (Bråthen et al., 2016).

Norway are obliged to follow EU standards, and so the European standards for BIM (which are actually ISO standards) makes up the main framework for BIM in Norway (BuildingSMART Norge, 2017). Norway has one national BIM standard in addition to the international and European standards, namely NS 8360 BIM-Objekter, which contains classification of objects and standards for connection of features and values to IFC models (Standard Norge, 2015). This was the first and only BIM-standard to be developed in Norway (Standard Norge, 2018). Another standard of interest is “Statsbyggs BIM-manual 1.2.1” from 2013, which is a standard with open BIM format used for public procurement of buildings in Norway. Statsbygg demands that all their projects use BIM, and so the industry must adapt and utilize BIM in order to do projects for Statsbygg. The manual is expected to be updated to version 2.0 in the near future, as it has been under development for several years and the work with finishing it is soon underway (Statsbygg, 2018). The 2.0 version will contain updated requirements and validation procedures of BIM models, and introduce the terms level of development (LOD) and level of information (LOI).

2.3 Life cycle assessment (LCA)

Life cycle assessment is a tool for analysing the environmental impacts of a product, while taking into account the whole life cycle of the product (ISO, 2006a). A LCA consist of four phases, and is typically iterated several times by constantly improving each phase based on the last iteration (Figure 10). The principles and framework of LCAs is defined in ISO14040, and the requirements and guidelines for LCAs is presented in ISO14044 (ISO, 2006a, 2006b). Detailed technical guidelines for LCA of a product is provided by the International Reference Life Data System (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010).

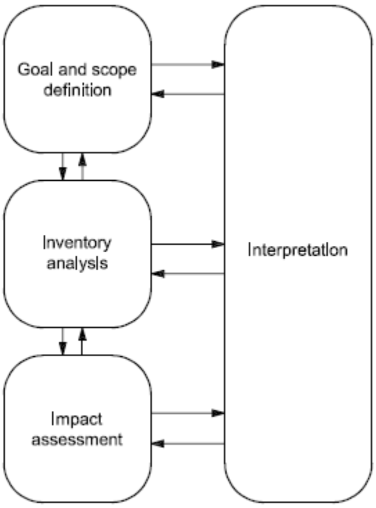


Figure 10: The four stages of a life cycle assessment, and their interaction with each other (ISO, 2006a).

LCAs can be attributional and comparative. Attributional LCAs calculate the actual environmental impacts caused by a product throughout it’s life cycle. Comparative LCAs calculate the change in environmental impacts from changing a system or replacing a product with another.

2.3.1 Whole-building LCA

LCA of buildings have some specifically defined frameworks for life cycle stages. These are presented in Figure 11.

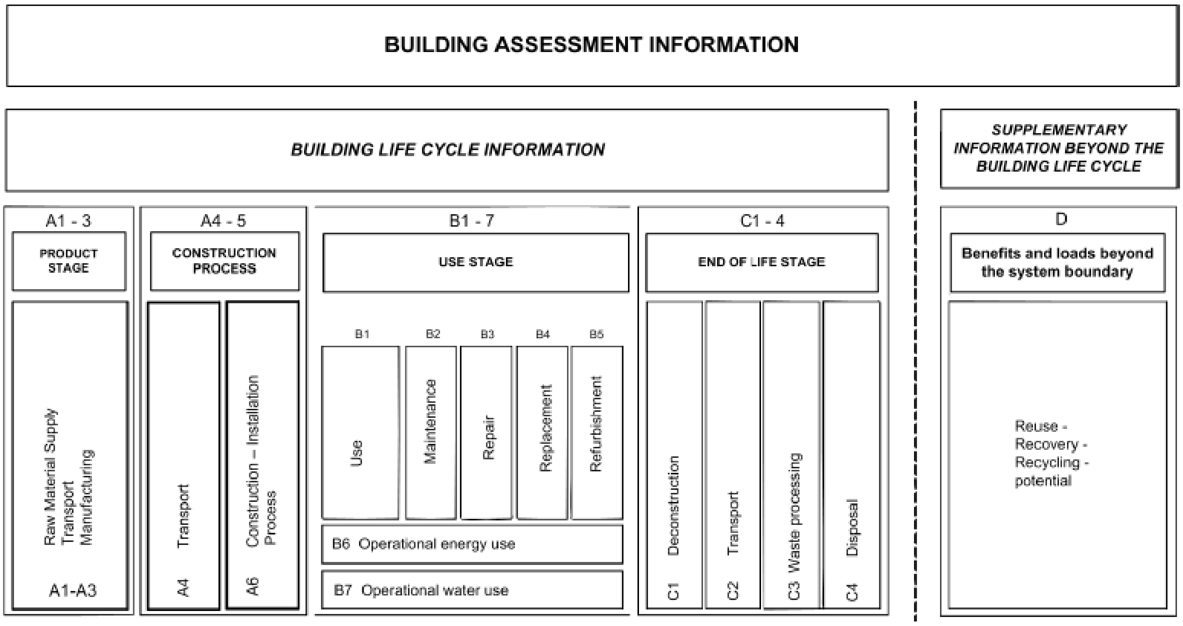


Figure 11: Definition of information modules according to Standard Norge, for LCA of buildings (Standard Norge, 2011).

Due to the complexity and uncertainty related to building LCAs, the construction sector can not perform LCAs of buildings with the same level of detail as other product are in other sectors (EeBGuide Project, 2012). Buildings have very long lifetimes with varying levels of refurbishment and multiple functions that can vary throughout the life cycle (Basbagill, Flager, Lepech, & Fischer, 2013). A complete LCA needs to cover all the information modules presented in Figure 11. A simplified LCA is required to include modules A1-A3, B4, B6, B7, C3, C4 and optionally D, and a screening LCA needs to cover A1-A3, B6 and B7 (EeBGuide, 2012; Meex et al., 2018).

2.4 BIM-based LCA

BIM-based LCA is a relatively new method used to simplify the process of compiling life cycle inventories. The method has become a standard tool for building LCIs in several construction companies that use BIM (Rist, 2018). The LCAs made from BIM data are typically used for documentation of building sustainability. Simply put, BIM-based LCA can be described as the use of quantity take-offs from a BIM model, which is used to build a life cycle inventory.

2.4.1 BIM-based LCA tools

The number of software programs that can be used to make LCI's based om BIM models is very extensive. This includes for instance energy simulation software such as IDA ICE, even though it is neither a BIM software nor a LCA program. Bueno et al. have recently made an updated list of LCA tools that have at some level of integration with BIM (Bueno & Fabricio, 2018). This list of BIM-LCA integration tools is shown in Appendix A, together with corresponding features and limitations identified by Bueno et al. The selected LCA programs "were chosen according to their availability, coverage and efforts towards incorporating LCA-based decisions in the early design stages" (Bueno & Fabricio, 2018). In 2011 there were no integration of LCA and BIM tools, and the list in Appendix A shows that there has been significant development since then (Rist, 2011).

A study has compared the results from a complete LCA study and a BIM-LCA plug-in called Tally, and found that the results were not consistent (Bueno & Fabricio, 2018). They found both absolute differences and relative differences in impact categories. They argued that the most likely reason is simplifications in Tally, to make it usefor for designers without knowledge about LCA.

2.5 BIM-based LCA in early design stages for buildings

LCA can be used as decision support during the design phase of buildings, a process that is less work intensive if life cycle data can be obtained from a BIM model (Meex et al., 2018; Rist, 2011; Soust-Verdaguer et al., 2017). One of the major differences between an LCA in early design stage versus a completed building is how developed the BIM model is. The difference in LOD leads to a difference in uncertainty, where lower LOD gives higher uncertainty. This leads to a dilemma, because the availability and certainty of data is low during the design phase, which is when decision support from LCA has the biggest impact.

The research literature contains several studies where BIM-based LCA was performed during the design stages of buildings (Soust-Verdaguer et al., 2017). None of these have achieved full automation for calculations or information transfer between software programs, but some studies have automated parts of the information exchanges. No studies with complete cradle to cradle scope are identified in the literature (when excluding research that is not considered to hold sufficient scientific standards to be included in this thesis). The studies are limited to simplified LCAs. Basbagill et al. developed a proof-of-concept parameterized optimization method based on BIM-enabled LCA results (Basbagill et al., 2013). The feasibility of implementing this specific method in practice has not been confirmed by more recent research, although parameterized optimization is promoted by many as the holy grail of sustainability optimization (Ghaffarianhoseini et al., 2017; Kreiner et al., 2015; Welle, Haymaker, & Rogers, 2011). Iddon & Firth performs a case study on BIM-based LCA during early design phase to compare four different design options (Iddon & Firth, 2013).

3 Methodology

The literature review for this thesis involves several topics and is based on both physical and electronic literature. The methodology is based on a framework proposed by Arksey and O’Malley, which has been adjusted to the specific needs for this thesis (Arksey & O’Malley, 2005). They present a methodological framework for several different types of scoping studies, two of which are used in this thesis; “To summarize and disseminate research findings” and “To identify research gaps in the existing literature” (Arksey & O’Malley, 2005). This referred methodology is specifically designed to include “all relevant literature regardless of study design”, which is especially desirable for the search topic “BIM LCA” because the research field is relatively immature, varied and explored by several research perspectives (architects, software developers, industrial ecologists etc.). The proposed stages for doing a scoping study include (1) identifying the research question, (2) identifying relevant studies, (3) study selection (4) charting the data and (5) collating, summarizing and reporting the results (Arksey & O’Malley, 2005).

The literature review was conducted from January 2018 to June 2018. Most of the searching was done before May, while the searching in May and June was done for a few search topics and a double check of the broadest search terms used before May to ensure that the latest research is considered. Electronic, scientific databases were the primary search arenas, including databases such as Scopus, Oria, Google Scholar and Science Direct. The searches were narrowed down by only including literature from year 2000 to 2018, and only literature in English or Scandinavian languages where language filtering was an option. Several search terms were used, all of which can be seen in Figure 12. Below follows a description of the process of acquiring information for the key topics in this thesis.

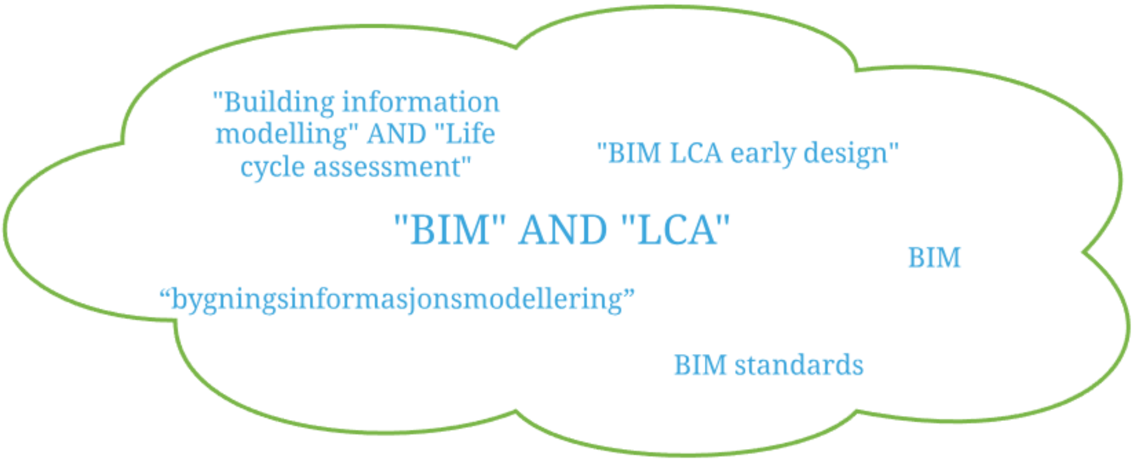


Figure 12: All search terms used in the literature review

When analysing the literature gathered from the literature search, the abstract was read first to decide if the article was relevant and worth studying in more detail. If there were still uncertainty about the relevance of the article, then the conclusion was read to find out more about the topic of the research and what the main takeaways from the research are. The relevant studies were then skimmed through in search of particular areas of interest. The areas of interest are presented in Figure 13. Several studies were read in detail, to fully understand the connection between methodology, results and discussion. Detailed reading also gives valuable insight on the limitations of some conclusions, due to assumptions and the scope for the research. Additional studies of interest were found when reading the relevant studies identified from searching.

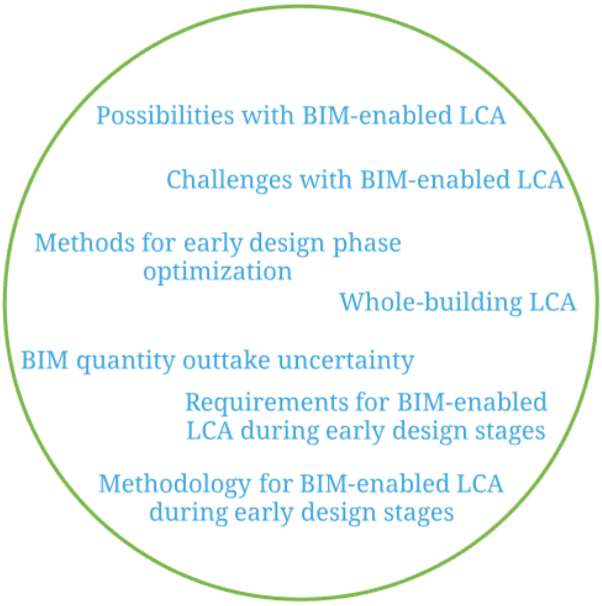


Figure 13: Special areas of interest from the literature review.

Several additional sources were identified through other studies. These were not found in a systematic manner, merely by being referenced in other literature.

3.1 BIM

Knowledge about BIM was primarily gained from physical books with comprehensive information about the principles, practices and standards. Four books were given to the author from the master thesis supervisor, and three more books on BIM were supplemented to this collection by visiting the architecture and civil engineering library.

A search for BIM standards was also conducted by reviewing the first forty search results given from the websites Google.no (search terms “BIM standard” and “BIM standards”), standard.no (search terms “BIM”, “bygningsinformasjonsmodellering” and “building information modelling”) and iso.org (search terms “BIM” and “building information modelling”).

3.2 LCA

This thesis is aimed at readers with basic knowledge about LCA, and so the theory presented in this thesis on LCA methodology is limited to the aspects that are relevant and necessary to give context and insight into the discussions in this thesis. If necessary for the reader, comprehensible and compact information about LCA and building LCA can be found in (Rist, 2011)

3.3 BIM-based LCA

This search topic was considered the most important for the thesis, and was therefore partly done with a systematic review methodology. Advanced searches that required both of the terms “BIM and “LCA” gave a varying number of search results with the different scientific databases. The results from Scopus, Oria and Science Direct all gave a number of search results varying from almost 200 to 450. All of these several hundred results were evaluated for relevance based on their title. The number of search results should ideally be lower, but by including more search terms there would be a risk of excluding important research. Relevant literature was downloaded directly. The abstract was read for certain search results to find out if they were relevant enough to be downloaded and studied in more detail. Search results that were obviously irrelevant were not downloaded or considered further.

The search for “BIM LCA” in Google Scholar gave a much higher number of search results than the other databases, with over 3000 hits. The search term was therefore specified to ““building information modelling” and “life cycle assessment””. This search term still yielded almost 900 search results. These search results were sorted by relevance, and only the title of the first 400 search results were considered for relevance.

Several of the studies relevant for BIM-based LCA are not considered to hold sufficient scientific standard and are therefore not mentioned or discussed in this thesis.

Knowledge about BIM-based LCA was also found in the master thesis “A path to BIM-based LCA for whole-buildings” from 2011 by Tobin Rist, by recommendation from the supervisor of that and this master thesis.

4 Results and discussion

4.1 BIM-based LCA

BIM-based LCA is adopted by LCA practitioners in industry for documentation purposes, and can be expected to become more common and conventional as the use of BIM becomes more widespread. Quantity outtakes from BIM provide significant reductions in the effort needed to compile LCIs. Current application of BIM-based LCA is characterized by significant need for manual work for transferring and adjustment of information between software. The level of automation is low, but advancements in automation is considered to be attainable. Some level of LCA expertise is currently required to perform information transfer and adjustment between software.

A general flow chart for processes and information flow in BIM-based LCAs is presented in Figure 14. The sensitivity step is often not needed for certification or documentation purposes, and is only presented as an option in the figure. BIM-based LCA for documentation purposes can be done according to LCA methodology for buildings. There is however some potential for uncertainty when comparing LCAs based on BIM models, due to varying modeling practices in BIM software. LCAs do not quantify uncertainty normally, and this added uncertainty should therefore be discussed in the LCA interpretation.

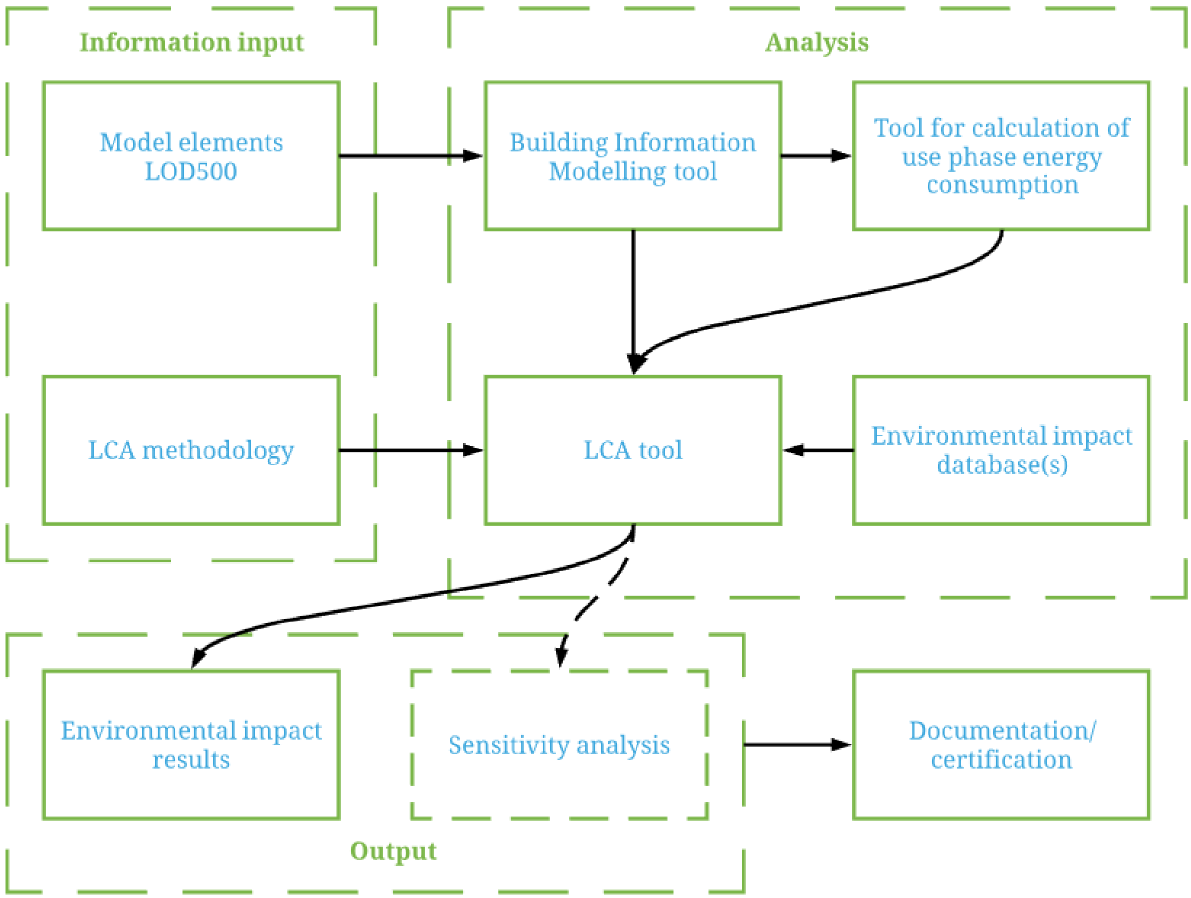


Figure 14: Processes and information flow for BIM-based LCAs.

4.2 BIM-based LCA in early design stages for buildings

Use of BIM-based LCA in the early stages of building designing is a complex topic, because it involves questions from several topics, such as LCA methodology, technological maturity, practical usefulness, expertise requirements and best-practice for sustainable building design. A general process chart is suggested in Figure 15, to enable a systematic evaluation of the requirements for BIM-based LCA in the early stages of building design. The required information input for such a process consist of LCA methodology and model elements at levels of development between LOD100 and LOD300. The desired design, represented by the model elements in the figure, are used to build a virtual model in a BIM tool. The BIM is then used to calculate use phase energy consumption. Data from the BIM model and energy simulation is then connected to representable processes in environmental impact databases through a LCA tool. The LCA tool calculates the total environmental impact for the building. A sensitivity analysis of change in environmental impact as a function of design parameters is not an absolute requirement, but is highly recommended. The LCA and sensitivity analysis provides information that helps the modeller make design changes that improves the sustainability of the building. Requirements related to these processes that are necessary to enable meaningful use of BIM-based LCA in early design stages for buildings will be discussed in the following sub chapters.

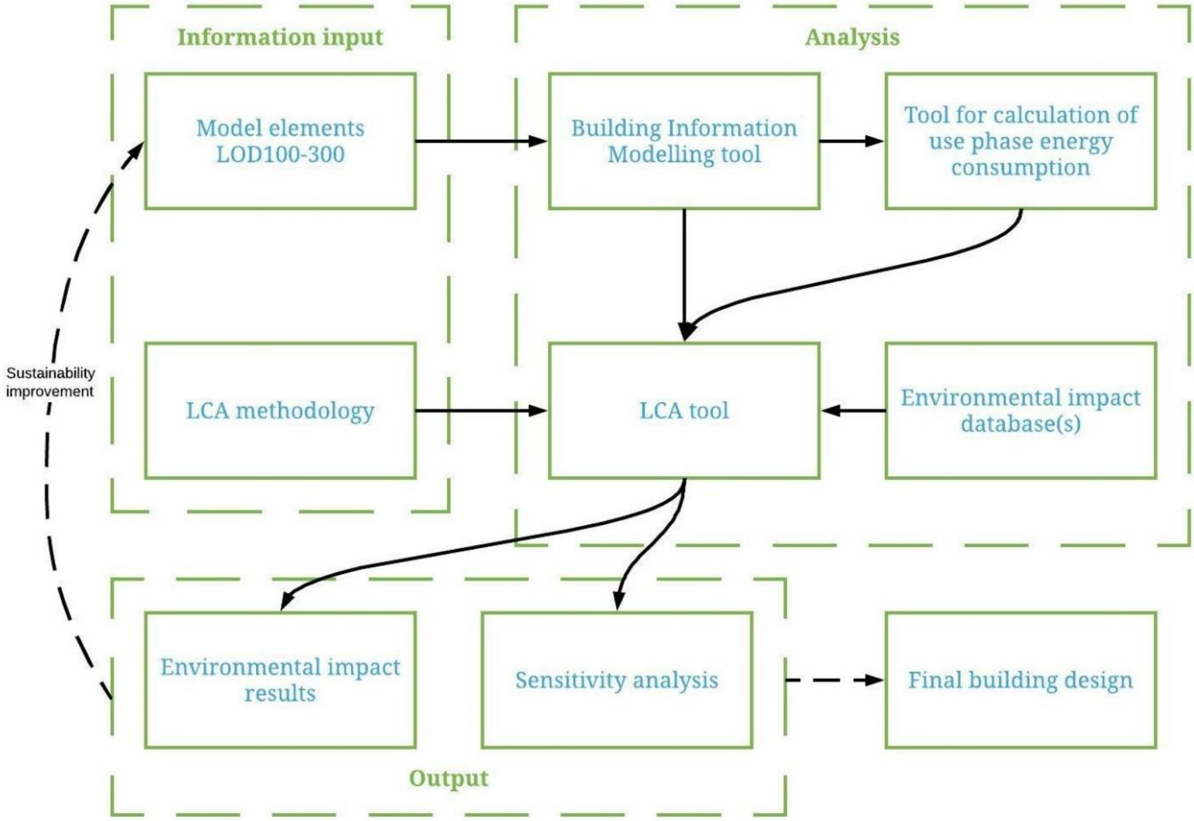


Figure 15: Processes and information flow for BIM-enabled LCA applied to early design stages for buildings.

4.2.1 Sustainability improvement potential

Using BIM-based LCA in the early design stages for buildings only makes sense if a significant improvement in sustainability can be achieved. This requirement is relevant for any sustainability measure, but is especially relevant for this method due to the high effort needed to apply it. Because it is currently a laborious task to apply this method, it should be compared to best-practice or certification schemes for building sustainability in the industry, because the most likely users aim for sustainability in the first place. It represents an increase in cost and effort, and should be compared with others measures that require additional cost and effort. Alternatively, the cost/benefit could be compared to other sustainability measures. Any quantification of improvement potential must also include both embodied emissions and use phase emissions for the buildings, because the relationship between the two are crucial for optimization.

First off, there must be actual improvement potential for a building with specified requirements built according to best practice. It is reasonable to assume that we have not yet perfected building practices, considering that they are still changing and are subject to guideline updates. Secondly, the use of BIM-enabled LCA must be able to discover this improvement potential early in the design phase. This could hardly be quantified for buildings in general, and would have to be verified with case studies, where the same building requirements and conditions were used to make a building design both with current best-practice and LCA based on BIM during the design phase to improve sustainability. Any trend in difference between calculated sustainability based on "as-built" LOD would reflect the improvement potential. The improvement potential could, however, vary for different building types, and should be treated accordingly. Current research does not compare their resulting improvement potential to best-practice.

There are limits to how low the emissions from a building can get, due to e.g. minimum living standards and legal requirements such as technical building standards, which is illustrated in Figure 16. The figure is a conceptual sketch, and the size and relationships between emission types are not representative.

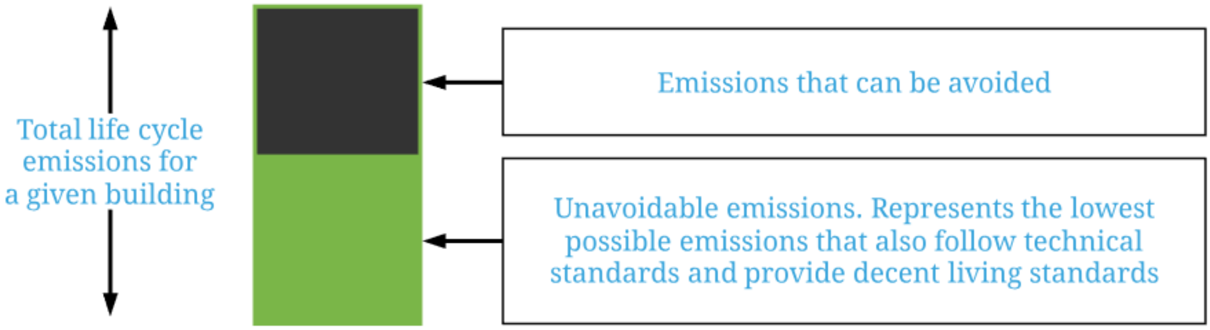


Figure 16: Illustration of the conceptual limits to how low the emissions for a building can get. Size and relationships in the figure are not representative, only conceptual.

The limitations of BIM-based LCA methodology to improve sustainability is not discussed in the reviewed literature. Some potential areas of building sustainability improvement are identified and explained in Figure 17. Only one of the three areas of improvement can be addressed with BIM-based LCA during the design phase for buildings. The second area of improvement include emission reductions for products, materials and energy used in buildings, and the third area of improvement include user behaviour during the use phase and adjusted user requirements. There is a difference between changing sustainability through optimizing material composition and improving the sustainability of these materials, and BIM-based LCA can not be used for the latter option in the process of designing a building.

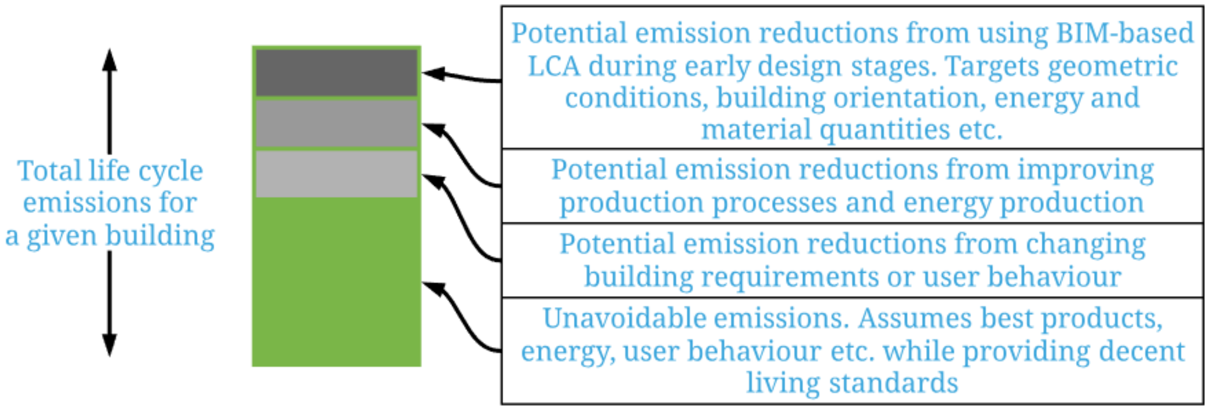


Figure 17: Illustration of the conceptual limits to how much the use of BIM-based LCA during the design phases can reduce emissions. Size and relationships between emission types are not representative, only conceptual.

If the process of making a BIM that is LCA compatible or the LCA process costs considerable resources or causes emissions through e.g. hardware or electricity consumption, these additional emissions should be reflected in the LCA, as both the negative and the positive contribution of BIM-based LCA should be accounted for. This is true both for attributional and consequential LCAs.

4.2.2 BIM level of development

Current practice in the AEC industry show that BIM-based LCA is a reliable methodology for completed buildings and high levels of development. With lower levels of development however, the uncertainty in LCAs is significant.

LOD100 corresponds well with the level of detail in the screening LCA method, and can only be used to make simple assessments based on generic values. Such an assessment could give some insight into impacts from major sub structures based on generic LCA values such as foundation, load-bearing structures, roof and walls with some options for materials, as well as impacts calculated from statistical/generic data on operational energy use such as kWh/m^2 (EeBGuide, 2012). It is impossible to optimize embodied emissions and use phase emissions based on such an analysis because they are not interdependent in the calculations. Building designers generally have some existing knowledge about the sustainability of different building materials, and therefore the added value from using such BIM-based LCA at LOD100 is limited.

Simplified LCA methodology covers everything above LOD100 and below LOD400. This corresponds to LOD200-300 as well as the smaller steps between the defined levels. The literature review identified that uncertainty in quantity outtakes for BIM models at low LOD is not sufficiently analysed. There are no quantified or approximate percental estimations of the uncertainty in BIM models with LOD100-LOD300. A comparisons of simplified versus complete LCA done by Bonnet et al. and Lasvaux & Gantner can not be linked directly to a LOD, but considering that they identified a 20% and 30% difference between simplified and complete LCAs indicate that there might be considerable uncertainty at LOD200 and LOD300 (Bonnet, Hallouin, Lasvaux, & Sibiude, 2014; Lasvaux et al., 2013). This does however not mean that the utilization of BIM-based LCA is useless, as it might help identify improvement potential anyway.

Future research should quantify the changes in quantity outtakes from BIM models as it evolves from LOD100 to LOD500. It is not necessarily possible to categorize a BIM model according to the LOD definitions because model elements might have varying LOD, but it is still possible to save and use several snapshots in the model pression to investigate quantity uncertainty.

Considering that the added detail to a BIM model after a BIM-based LCA is performed probably is related to different materials, there might be considerable changes in environmental impact and possibly a shift in impact distribution between environmental impact categories. To exemplify this point, lets assume that a BIM-based LCA is performed somewhere between LOD100 and LOD200 and results in some climate change impact from the use of wood. When the BIM model is developed further, more specified model elements are added. This could for instance mean that a generic wood type is replaced with impregnated wood, a heavier wood type or a wood type that requires more paint. This could increase e.g. the ecotoxicity or increase the GHG emissions. The development of LCA results throughout the development of BIM models should therefore be investigated in future research.

The application of this method around LOD200 is probably meaningful, but needs more research to confirm that sustainability improvements identified at LOD200 are actually achieved when the building is constructed. Also, the representation and discussion of LOD in the literature does not reflect how real BIM models have several design packages at different LODs and floating definitions that fit in between the six levels of development defined by the AIA.

4.2.3 LCA methodology

BIM-based LCA performed during the design phase for buildings can be considered a simplified LCA according to EeBGuide classification. With application during the design phase, such a LCA is very different from LCAs done for documentation purposes, from the fact that it is only supposed to as a tool for sustainability improvement. It will not be used for documentation purposes, and so there is limited need for comparability with other building LCAs. As long as the use of LCA during early design stages for buildings is verified to be effective as a tool for reduced emission and confirmed through a LCA based on LOD400 or LOD500, there might not be a need for standardized LCA methodology for BIM-based LCA used to improve life cycle sustainability in buildings during building designing.

4.2.4 Software integration

The integration of all the necessary software is considered to be one of the most important challenges for implementing BIM-based LCA early in the design process of a building (Antón & Díaz, 2014; Soust-Verdaguer et al., 2017). This refers to the integration of BIM software with a virtual model to energy simulation tools, LCA tools and environmental impact database(s). The integration of these tools into one platform could drastically reduce the required work load and time required to perform an LCA, which would lower the bar for implementing BIM-based LCA during the design phase of buildings. It would also decrease the requirements for expert knowledge about energy simulation tools and LCA tools.

The best software integration solutions that are currently available still require some level of manual export and import of files, as well as specialized BIM naming standards. The current status for software integration means that a lot of time and expertise is required. Widespread adoption of IFC standards and IDM standards throughout the information chain from architect to LCA practitioner/BIM manager would contribute to unlock some of the potential for better software integration. The BIM practices performed by several architects today limit the integration of BIM models into plug-ins and other software, which is a barrier that can be solved by consistently complying with standards.

4.2.5 Sustainability improvement methods

The literature presents several methods to improve sustainability of buildings based on LCA results compiled from BIM models from the design phase. It can be argued that none of them manage to capture the actual level of sustainability for buildings, and that they would not be viable for industry wide standardization. The use of sustainability criteria is also discussed.

4.2.5.1 How should building sustainability be evaluated?

The research on BIM-based LCA is heavily focused on GHG emissions and climate change potential, and therefore addresses only one of the several aspects of sustainability. LCA communities and practitioners are generally very cautious of ranking the importance of different sustainability criteria, but many in the AEC industry seem to have set their minds on focusing on climate change and emissions of CO_2-equivalents. This is probably in response to the obligations towards the two-degree target set by the Paris Agreement and the corresponding pressure from governments and other stakeholders. Addressing the challenge of climate change is without question crucial, but it is also important to be mindful of the potential for problem shifting. It is however extremely challenging to establish standards for how environmental impact categories should be compared and weighed against each other. It is therefore also difficult for the building industry to know what impact categories they should focus on improving, and with that perspective it is easy to understand that they focus on an impact category that has massive political backing and legally binding goals such as climate change potential.

The use of one or several midpoints, endpoints or single score for environmental impact is possible, but this is far from likely to be implemented. This would require agreement for the weighing of impact categories as well as cultural perspectives reflected in e.g. the hierarchical, egalitarian and individualist perspectives from ReCiPe. Normalization of these indicator types is also probably out of the question, because normalized indicators only reflect the environmental impact we have today and does not reflect preferences for the distribution of annual environmental impacts.

Another option to measure the sustainability of buildings is to use benchmarks. These could be benchmarks for one or several midpoint indicators that rank the building sustainability from poor to good. This would require benchmarks for several building types, considering that there can be big variations in environmental impact from different building types. It would be difficult to decide on these benchmarks, and a lot of LCAs would have to be performed to collect the necessary data for each building type. Such a method might also require separate benchmarks for different nations. The use of benchmarks would also fail to consider that each project is built in varying and specific local environments. The improvements in sustainability for a specific building can be severely limited by the local conditions and the requirements set by the owner.

Another option that is possible (but unwise) is to establish national legal requirements with maximum thresholds for one or several impact categories. This would however not give incentives to optimize sustainability performance, but rather force poorly designed buildings to improve. It would also require all building projects to perform LCAs during the design phase, which is far from reasonable with today’s level of BIM adoption and maturity.

4.2.5.2 How can building sustainability be improved?

Several studies discuss how the results from a LCA can be used during the designing of a building. Previous research has proved that it is possible to use BIM-based LCA in early design phase to reduce GHG emissions for case studies that are not based on best-practice for building design. The feasibility of achieving substantial emission reductions by applying BIM-based LCA during building designing is evaluated to be relatively low for preliminary designs made according to best-practice. Some potential for emission reductions is however expected to be achievable for buildings designed by designers with limited knowledge about building sustainability. No studies have considered other impact categories than climate change in such efforts to improve building sustainability.

Building LCAs are generally used calculate the total impacts from a building, and communicates the results in several ways. Some useful examples include:

- Total impact for all midpoint and endpoint categories
- Distribution (and ranking) of total impact over the building’s life cycle stages for one or several impact categories

- Distribution (and ranking) of total impact over the components in the building for one or several impact categories
- Distribution (and ranking) of total impact over the materials (database processes) in the building for one or several impact categories

An LCA practitioner with knowledge about building sustainability could use the results to look for emission hot spots, and would also be able to notice if results deviate from normal values. Emission hot spots and unusual results can then be investigated for improvement potential.

Another tool that LCA practitioners often make use of is sensitivity analysis. Sensitivity analysis gives information about percental change in emissions from a percental change in parameters. The parameters are linked to e.g. material quantities or properties. The sensitivity analysis can be used to identify parameters that give significant emission reductions, and the LCA practitioners can then focus on altering these design aspects.

provides information about life cycle impact distributed over life cycle stages, materials and objects/processes, and gives the modeller information about what design alterations that.
and sensitivity analysis provides information about how much each material, life cycle stage, object/ process

Several studies discuss the use of visualization in a digital model (Meex et al., 2018; Röck et al., 2018). The general idea is that colour coding of model elements can reflect environmental impact. Röck et al. presents a method with accompanying proof-of-concept where model elements are colour graded according to the improvement potential from exchanging this model element class for a type with (in this case) lower GHG emissions. The presented method has a crucial weakness by not accounting for the use phase emissions. This could possibly be done however, by running energy simulations for all the model elements classes available and feeding this information into the digital representation software. Meex et al. argues that this is one of the most useful methods for achieving improved sustainability with BIM-based LCA. With automated LCA calculations based on a BIM, this is probably possible to achieve.

In the event that use of BIM-based LCA in the design process would identify emission reduction potential, it is possible to attribute the emission savings to known optimization principles. Optimization principles for buildings are well known in the AEC industry already. It would for instance not come as surprise if the use of BIM-based LCA concluded that a building consumes less energy if it was shaped as a multi story cube instead of a one story tall building with the same floor area shaped as the letter H, because it is well known that higher volume to surface area ratio reduces conductive heat loss. It can therefore be argued that building designers with good knowledge of these criteria would leave little room for sustainability improvement if they focused on maximising building sustainability. This is especially true for small and simple buildings, but it might be more challenging to apply these principles for more complex buildings. This means that the potential improvement potential from using BIM-based LCA during building design phases might be bigger for more complex buildings.

4.2.6 Practical applicability for industry stakeholders

With all the requirements presented above taken into consideration, the author finds it likely that BIM-based LCA will be used during the early stages of building design to some extent in the future. Early adopters are already using it to some extent (Rist, 2018), but is uncertain whether this is used to reduce emissions. The methodology is most suitable for building designers that care about decreasing environmental impact or want to achieve some form of certification. The incentives for adopting this method to reduce climate change impact is considered to be weak. It is not a legal requirement, clients do not (yet) demand it, and to the author’s knowledge there are no certification systems that require it.

Better software integration and automation will decrease the time and expertise needed to perform BIM-based LCAs, and is expected to increase the adaption. Increased standardization among BIM practitioners is required to unlock better integration and automation, which might come at the cost of additional training for employees. Building designing is already very complex, with many decisions, calculations and several designers that often work in parallel in separate companies, and standardisation of BIM practices is therefore crucial to enable BIM-based LCA during the design phase. Architects are central to this work, because they lay the foundation that others use and work with to in BIM tools. Additional software programs also incur additional cost and training. Methodology for how to perform BIM-based LCA with focus on GHG emissions exist, and have proven in case studies that it can work. The potential gains are probably relatively small for professional building designers with good knowledge about building sustainability, but the potential gains increase as the knowledge about building sustainability decreases. LCA expertise is required until the process becomes more user-friendly and automated.

When buildings modelled with BIM are refurbished in the future, there might be good possibilities for utilizing BIM-based LCA of different refurbishment options. Having a BIM for the building is an opportunity to do relatively small changes in the BIM and calculate the emissions embedded in the new materials and the resulting operational emissions for the assumed remainder of the lifetime of the building.

If automation of LCAs from BIM is achieved, it can be used to of for automatic parameterized optimization of building sustainability based on LCA results. This could be a very powerful tool. Especially so with a large variety in possible designs from BIM, which might be obtainable from artificial intelligence in the future. This topic is however outside of the scope for this thesis, and will probably be addressed in future research.

5 Conclusion

After several years of reducing energy consumption from new buildings, best-practice for building design is approaching an equilibrium where the embedded GHG emissions from adding more insulation do not improve total GHG emissions. The embedded emissions are bigger than the potential reductions in energy consumption in the use-phase and the corresponding GHG emissions. The work of further improving building sustainability practices has therefore become more difficult and complex. This thesis investigates a relatively new method to further improve building sustainability, namely the use of BIM-based LCA in early design stages. Practical and methodological requirements for such a method is identified and evaluated for feasibility in this thesis.

An extensive literature review on the topic of BIM-based LCA was performed, which revealed several research gaps. The literature does not contain a holistic methodology for BIM-based LCA in the early design stages for buildings. The mentions of LCA methodology for BIM-based LCA is limited, and not sufficiently discussed. Uncertainty in BIM models with low level of development is not quantified or sufficiently addressed. Several papers present proof of concept studies based on case studies that achieve lower GHG emissions after evaluating emission sources and then adjusting design. These studies are not compared to other sustainability improvement methods, and it is therefore still uncertain whether this methodology holds any promise to become best-practice. This thesis adds to the existing literature by evaluating broad methodological aspects of this method and exploring the benefits and challenges of using it.

A general process and information flow concept for BIM-based LCA is proposed for both documentation purposes and the early design stages for buildings. Several requirements not mentioned in BIM-based LCA research are identified and discussed in this master thesis. The research topic is complex, and involves several research areas and disciplines, and therefore the development of a full methodological framework needs more research. The concept of using BIM-based LCA during early building designing stages to improve sustainability is considered to be feasible, but probably not practically viable for the AEC sector with the current level of software integration, insufficient incentives and high expertise requirements. This thesis proposes that a rigid or standardised LCA methodology is probably not required for BIM-based LCA during the designing of a building, because such LCAs will only be used to improve sustainability, and will not be needed for documentation or other comparison with other LCA studies. It must however be proven that it actually leads to improved building sustainability.

Future research should investigate the uncertainty of quantity outtakes from BIM during low levels of development such as LOD100, LOD200 and LOD300. Another important question that should be addressed is how the AEC industry should improve building sustainability with respect to weighing between environmental impact categories.

6 Further work

The feasibility of full integration of BIM software with energy simulation software, LCA programs and environmental impact databases should be investigated. If this is possible, automation of LCA results from BIM models could make BIM-based LCAs accessible to designers without LCA expertise, and improve the cost/benefit ratio of implementing BIM-based LCA during early design stages for buildings to improve sustainability performance.

It is becoming increasingly difficult to improve sustainability in buildings. Academic research should identify the remaining improvement potential and compare it to best-practice, average practice and/or technical standards for new buildings.

Methodological standards for sustainability criteria should be developed for the building sector, to avoid unwanted problem shifting to other impact categories from narrow-eyed focus on green house emissions and climate change.

The uncertainty in quantity outtakes from BIM models should be identified for several levels of development. This information is not sufficiently known today, and increased knowledge could improve both cost estimation and BIM-based LCAs.

Methodology for parameterized optimization for building sustainability is currently under development. Future research should investigate if and how this methodology can be further enhanced with automated BIM-enabled LCAs. If such parameterization optimization becomes feasible with multi-criteria optimization, the literature should discuss the weighing of environmental impact categories which models are optimized for.

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Appendix A

Table 2: BIM-LCA integration tools, with corresponding features and limitations (Bueno & Fabricio, 2018).

BIM-LCA Tool Institution, Country	Features	Limitations
Elodie Centre Scientifique et Technique du Bâtiment (France)	• Simplified LCA compliant with European standards. • Design alternatives can be compared, • Energy performance in the design and construction solutions, • Environmental impacts assessment at the construction site, • Computation of transport of users and of major environmental contributions.	• Separate software, needs to import data from BIM File, • Software –most of the information is only available in French.
eTool LCA International Team Effort (Australia, UK, Brazil, Germany)	• Detailed reports with comparable information on environmental data, • Multiple Impact Reporting, including CO2, Cost, Energy, Water, Land Use, Ozone Depletion, Human Toxicity. • Web-based software, with a pay-as-you-go certification, reviewed by third parties, • Compliant with ISO 14044 and European Standards.	• Separate software, needs to import data from BIM File; • Free version does not allow the user to print the assessment reports.
Green building assessment tool (GBAT) Istanbul Technical University, (Turkey)	• The framework builds a relationship between the BIM and the green building rating processes. • The framework builds a relationship between the BIM and the green building rating processes. • IMPACT Compliant assessments, including BREEAM credits.	• Separate software, needs to import data from BIM File, • Presents the available credits limited to only a subset of the available BREEAM materials, • The material database cannot be automatically updated from the BREEAM database and there is manual effort to convert it to the materials library.
Green Building Studio® Autodesk (USA)	• Carbon emissions report, • Energy analysis of complete buildings, • Daylighting, Water use and related costs and natural ventilation analysis, • Cloud-based software, • It can be used as a support tool for impact assessment of the building operation phase, • Support for LEED and Energy Star certifications.	• Very broad thermal and energy balance software, not only dedicated to LCA studies, • Does not perform full LCA studies, • Separate software, needs to import data from BIM File.
Impact Compliant Suite IESVE (United Kingdom)	• LCA compliant with British standards, • Integrated LCA, Life-Cycle Costing (LCC) and Capital Costing (CC), • IMPACT Compliant assessments, including BREEAM credits, • BRE ecopoint output.	• Separate software, needs to import data from BIM File.
LCA Design™ (Ecospecifier) National Research Center on Sustainable Built Environment (Australia)	• A single ecopoint score, • Choice of environmental inventory, impacts and point-score measures; • Comparative ecoprofiling at all levels of design, • Detailed graphical and tabular outputs • Cost variations, • Compliant with ISO Standards	• Difficulty in finding detailed information about the software and the data and methods applied on it, • No trial version available for testing so far.
Lesosai Several institutions, notably the Solar Energy and Building Physics Laboratory of Ecolepolytechnique fédérale de Lausanne (Switzerland)	• Basic version of building LCA, directed mainly to Switzerland, France, Luxembourg, Italy, Germany and Romania, • Calculation of environmental impacts from energy consumption from building operation, • LCIA methodology according to the Swiss standards, • Database updated by the materials producers, • Unlimited time use for free Demo version.	• Separate software, needs to import data from BIM File, • Very broad thermal and energy balance software, not only dedicated to LCA studies, • LCA studies are regionally specific; • Demo version does not allow to print the assessment reports;
One Click LCA Bionova (USA)	• Simplified LCA, • Compliant with BREEAM, LEED, HQE, DGNB and other certification schemes, • Integrated building site impacts and life-cycle cost (LCC), • Environmental Product Declarations (EPD) database, • Verified by third parties.	• Difficult do find information.
Tally™ Kieran Timberlake Innovations in partnership with Autodesk and PE International (USA)	• LCA for the whole building or a comparative analysis of building design options, • Identification of the largest environmental impacts and their comparison between the different materials and design options, • As a Revit plug-in, it allows the user to perform LCA within BIM environment, with no special modelling practices, • Available information on applied data and methods, and complete tutorials, • Flexible non-commercial licenses, • Intuitive and user friendly interface.	• It is specific for Autodesk Revit software, • The inventory data as the LCIA methods cannot be changed or updated by the user.