# Life Cycle Analysis of Buildings: A review

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## 1 Introduction

In the work for sustainable development one of the most important problems to tackle is climate change. Human activity has been concluded to have a significant influence on the climatic system, and the changes since the 1950's are unparalleled as compared to last centuries and millennia [1]. The International Energy Agency IEA states that around 1/3 of the global final energy consumption is used by the construction sector, leading to 15% of global CO2 emissions [2]. Sartori et al. [3] mentions 40%. In Belgium the construction sector accounts for 40% of emitted CO2 [4]. For Sweden specifically the National Board of Housing, Building and Planning (SNBHBP) states that the construction sector accounts 34% of energy use and 21% of greenhouse gas (GHG) emissions [5]. The building sector can be concluded to be a major contributor to GHG emissions. Other environmental aspects affected by the building sector are water consumption, ozone depletion, eutrophication of water bodies and toxicity. In order to be able to approximate the total environmental impact a building has over its life cycle it is important to have tools to quantify the environmental impact of the building, considering all aspects of environmental impact. A Life Cycle Analysis is one way to do this [6].

Life Cycle Analysis (LCA) is a way of evaluating the environmental impact of a building from a whole-scale perspective, taking into consideration raw material recovery, material production, transportation, construction, energy use in the building and aspects of demolition and reuse/recycling of materials, depending on the scope of the LCA. To reduce carbon emissions, energy usage and economic costs are common reasons for LCA conductance [7]. Several aspects of environmental impacts caused by a building and its related processes can be considered. Khasreen et al. [6] conducted a literature review of the LCA research area and lists a series of LCA articles and what environmental impacts those articles have considered in their respective LCA. Commonly considered environmental impacts are Energy Consumption, Global Warming Potential and Acidification. A motivation for conducting LCAs is that by conducting it before or in connection with the construction of a new building informed decision making by politicians, land lords and construction companies regarding materials, energy systems and other parameters are facilitated [8].

Several standards have been established over the years to standardize the practice of conducting LCAs. Noteworthy are ISO 14040, that have come in updated versions since the original one in 1997 [6] and outstakes a four step approach for how to conduct LCAs, and EN15978- standardizing a protocol for how to establish concepts such as functional unit, reference study period, system boundaries and how to divide processes and their environmental impact into modules [3]. A ”substandard” to EN15978 is the EN15804. It sets standards for how to produce Environmental Product Declarations (EPD:s) for construction materials and facilitates transparency and comparability [9]. In step 2 and 3 in ISO 14040, collection of data and calculations of environmental impact is carried out. Here, three approaches are commonly encountered in the research, The process-based approach, Input-Output (I-O) approach and the hybrid approach [10, 11]. The process-based is the most established approach [11]. It assesses environmental impact according to energy and mass flows, process by process. This requires system boundaries to be set, which may lead to truncation errors due to some processes being excluded [11]. I-O based approach originates from purchase-sales matrices from industries and uses the same thinking applied to the environmental impact. Truncation errors is not a problem here since transaction matrices describes how one monetary transaction in one sector can create another monetary transaction another sector. Aggregated errors are a problem though due to emissions for one specific monetary transaction being comprised of weighted average of sectors included in that transaction. I-O tables often assume same production procedures for domestic and non-domestic production which is another error source, as well as linearity assumptions [11]. Hybrid LCA is an approach to fill in the gaps left in process based and I-O methods, buy subjectivity in establishing boundaries between the process based and I-O methods to establish the hybrid method leads to hardships and uncertainties in comparing results [11]. The hybrid version has gained popularity in recent years [10].

LCA is one of several tools for Environmental Impact Assessment of buildings. Others are for example certification systems such as Green Building Rating Systems (GBRS), Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM). These GBRS:s are checklists, for which if a building checks for, can certify buildings according to its energy standards or environmental performance. LCAs however, can be conducted before a building has been constructed, thereby allowing for informed decision-making by building companies and politicians before construction. The two mentioned GBRS:s also incorporates LCA into their assessment system, giving a building higher grades/points if it comes with an LCA. An important type of document to mention within the LCA concept are Environmental Product Declarations, EPD:s. Manufacturers of construction materials disclose the environmental impact of their products in these EPD:s, and they can therefore be used when conducting LCAs of buildings [3]. This report provides a literature review on LCA focusing on challenges and possible solutions in use of LCA to reduce the climate impact of buildings.

# 2 LCA Standards and calculations tools

## 2.1 Standards

The ISO 14040 series establishes a 4-stage method for how to conduct a LCA, with the four stages being 1. Goal and Scope; setting system boundaries for the LCA, 2. Life Cycle Inventory; constituting of the collection of data and insertion of this into a calculation tool of choice, 3. Life Cycle Impact Assessment; here the environmental impact is sorted into categories and 4. Results interpretation and presentation; here the outcome of the environmental impact is discussed and presented. The results can be presented both qualitatively and quantitatively, and comparisons to other buildings and references can be made. This phase can work as a basis for conclusions and be informative for decision making [3, 11, 12, 13].

The EN15978 standard shows and sorts the stages in a building's life cycle into modules. It establishes the processes that should be considered when conducting a life cycle analysis [3, 14]. Figure 1 illustrates the modules, going from A to D.

| | | |
|---|---|---|
| A | A1-3 | Raw material supply |
| | | Transport |
| | | Manufacturing |
| | A4-5 | Transport |
| | | Construction-Installation process |
| B | B1 | Use |
| | B2 | Maintenance |
| | B3 | Repair |
| | B4 | Replacement |
| | B5 | Refurbishment |
| | B6 | Operational energy |
| | B7 | Water Use |
| C | C1 | Deconstruction/demolishon |
| | C2 | Transport |
| | C3 | Waste processing |
| | C4 | Disposal |
| D | | Reuse, recovery, recycling potential |

**Figure 1:** Modules in EN15978, adapted from [3, 15].

## 2.2 Tools

In order to conduct a LCA, calculations tools can be helpful. Sartori et al. [3] looked at a few calculating tools for LCA, namely Etool (Australia), OneClick (Finland), Athena (US), Tally (US) and Caala (Canada). Their article discusses the problem with lack of insight in the databases that the calculation tools uses and how that problematizes comparisons between LCAs if they have been conducted with different calculations tools. They also note that depending on the calculation tool a buildings' environmental performance for different certifications can differ. Below a few tools are described with more specifics.

**eTool** is a web-based tool that complies with EN15978 and ISO14040 standards. It can report on several environmental parameters, not only CO2 and climate impact but also for example ozone depletion, land use, water use and toxicity, making it a broad tool for LCA analysis. Some data must be chosen from default values and no EPD:s are included in the tool, they have to be imported externally. It is an open access, online based and free tool [3, 16, 17].
**OneClick** is another calculation tool for LCA. It is an extensive software and includes both databases of EPD:s and generic data for materials from specific producers and also allows the user to customize their choices. There is some insight into how the software handles the input data and calculates the results. LEED and BREEAM are among 40 certification systems that it complies with. Design drawings can be imported and the tool then analyzes the materials from the imported design drawings. It is extensive and flexible. It is a licensed tool but limited access can be given through different kinds of free licenses [3, 8, 17, 18].

An example of a Swedish calculation tool is **BM- (Byggsektorns Beräkningsverktyg)**, the Swedish Building Sectors Calculation Tool. It is restricted to the construction phase, (A in EN15978) and includes no EPD:s. The materials included are mostly linked to the foundation of buildings since the Swedish certification "Miljöbyggnad" mostly focuses on foundations, and

BM complies with ”Miljöbyggnad”. EPD:s can be put as external input data by the user. BM is a free tool [17, 19].

Östling [17] conducted a comparison between the above three calculation tools. She found that using generic data for material resulted in significant differences in the calculated CO2 emissions from the construction phase- and therefore stressed the importance for harmonized databases for comparisons between LCAs to be of better quality.

Another LCA tool tool available is **SimaPro**. According to SimaPro themselves, their software is transparent with calculation methods and data in their databases, and is suitable for several tasks such as climate declarations, sustainability reporting and generating EPD:s [20]. It is used by consultancies and universities in 80+ countries. They claim that their tool is suitable for collecting, monitoring and analyzing the sustainability performance data for services and products. Three different licenses exists, differing expertise level [20]. In a review over LCA research, Bahramian et al. [10] found that SimaPro was the used calculation tool in 40% of articles.

# 3 Climate impact from buildings and their life cycle cost

The connection between lowering carbon emissions through energy efficiency measures or material choices and the life cycle cost (LCC) of a building depends on several factors. Kniefel [21] investigated, through simulations and an integrated design approach, the cost-effectiveness of energy efficiency measures applied to a building under varying circumstances. He investigated 12 prototypical buildings with 3 building designs with 576 energy simulations dispersed over 16 cities. The simulations were of the energy consumption. The findings were that it is cost-effective to consider energy efficiency measures to buildings, especially when looking at longer payback periods. Energy efficiency measures, that lowered energy use and therefore direct energy costs, also allowed for physically smaller devices of for example HVAC equipment to be installed, thereby lowering costs in the installation phase of construction. Conventional energy efficiency measures were effective in lowering energy usage in new commercial buildings, by up to 40%. The cost effectiveness of applying energy efficiency measures increased as a cost on carbon emissions was considered, and therefore both the effectiveness in lowering carbon emissions and the economical cost effectiveness proved to be the best in areas with carbon intense energy production [21]. Kniefel [22] extended the study by Kniefel [21], still with 12 prototypical buildings and 3 building designs, but with 8208 energy simulations dispersed over 228 cities. In general, the results showed that for commercial buildings, using an integrated design approach to apply measures for increased energy efficiency reduced energy use and thereby costs related to energy use, in a cost-effective manner. The ASHRAE 90.1-2004 building design standard was the baseline building standard design in the study, and over a one year study period it was the preferred design, from a LCC perspective, in 52% of the combinations of building and location. Extending the study period to 10 and 25 years, it was the preferred design for only 17% and 6% of the building-location combinations. The carbon footprint of the building, with the energy efficient design, could be reduced by up to 43%, and by 25% on average. The extensive investigation with data points in 228 US cities allowed for a map to be created for comparisons on regional and state-wide level (in the US). It showed that reduced energy use does not necessarily in all case lead to LCC savings. Depending on the building design reasons for this was that lower capital costs for smaller HVAC-units did not offset higher initial investment costs for more insulation, as well as relaxed restrictions on windows between certain building standards investigated [22]. The study shows the complexities of LCC analysis and that energy related carbon emissions, LCC, energy use and resulting energy cost can vary by location. Even within the same climate zone and state the cost-effectiveness can differ, and so the above cited research shows the importance of being thorough and specific when conducting these types of analyzes, using location specific data on climate, construction costs etc. Ulubeyli et al. [23] investigated, in a literature review, the benefits and LCC of green roofs, and found, as in Kniefel [21, 22] that the LCC and other cost benefits are highly situation based and that a case-to-case perspective with good precision of the data to the local level is needed to get a good LCC estimation. Islam et al. [24] concluded that time-span of an LCC investigation can affect the accuracy of the LCC due to hardships in predicting and accounting for inflation and discount/interest rates over longer time-frames. They reviewed LCA and LCC research and the connection between the two concepts and also conducted a case study of their own. Their findings regarding affects on outcomes from the reviewed research and their case study were that the construction phase affected the outcome for LCC the most, whereas construction- and operation phases affected GHG and Cumulative Energy Demand (CED) category outcome the most. LCC were sensitive to discount rates. When looking at LCC and LCA in combination, system boundaries, life-span, climate and scope of the investigation were parameters that were important to consider for robust results [24]. They noted that there is a lack of research within the area of LCC and LCA in relation to each other.

On the area of cost-effectiveness of energy efficiency measures, there are several articles investigating effects of changing particular building components. An investigation of the life-cycle cost of green roofs as compared to conventional roofing systems was conducted by Carter & Keeler [25]. Their findings were that the net present value NPV were higher for green roofing alternatives than conventional alternatives. They note though, that they had assumed a worst-case scenario regarding the economics of the green roof alternative, and that their investigation had been limited to the Tanyard Branch watershed in Athens, GA, meaning that changing assumptions in their analysis, regarding for example storm-water protection measures and energy cost rises, the green roofing alternative can be the most cost effective in the end. They note the potential of green roofing to be used as a tool to control and manage storm-water problems as it is a non-invasive method from a land-use perspective since it does not alter the land-use of the urban area. In contrary, Davis [26] found that green roofing had a significantly lower LCC than conventional roofing when looking at NPV over a 50-year calculation period. He considered the conditions in the Netherlands and Switzerland, and found that the respective NPV costs for green roofing alternative were 16-26% lower that conventional flat roofing for the Netherlands and 27-37% lower than conventional flat roof for the Switzerland case. He notes that stormwater fee reductions, energy savings and municipal incentives helps in making green roofs more cost-effective. Green roofing can lower energy costs of older buildings that have a default bad insulation as compared to more modern buildings by improving insulation thereby lowering energy costs.

Regarding other building materials and their life cycle environmental impact, Praditsmanont & Chungpaibulpatana [27] conducted a case study of the Main Hall at Shinawatra University for different material configurations and found the light-weight and highly insulated envelope to lower the costs of the building structure and lowering investment and operating costs of the air conditioning system. A significant increase in investment cost for the envelope material was observed with the light-weight envelope material. This cost was offset, though after only 3-5 years, with the help of lower thermal transmission into the building with the light-weight material, thereby lowering need for air conditioning and therefore energy use. Cetiner & Ozkan [28] looked at glass facade materials in moderate climate areas such as Istanbul, and compared energy efficient configurations and their cost effectiveness. They found for their glazing materials that double facades were more energy efficient but that single facade alternatives were more cost effective.

Regarding retrofitting measures to lower energy use in buildings, Kumbaroglu & Madlener [29] investigated what parameters affected the economic feasibility of retrofitting for increasing energy efficiency of buildings. They looked at a particular office building in Germany for their case study and concluded that energy prices significantly affect the economical profitability and incentive for energy efficiency retrofits of buildings, with high volatility of energy prices making it more profitable to postpone retrofitting. If a change in the energy carrier is plausible it can also be advantageous economically to wait with the retrofitting. Caccavelli & Gugerli [30] developed a methodology to use a developed tool (TOBUS [31]) for looking at important parameters when considering retrofitting of office buildings, including indoor air quality, energy use deterioration and also giving the costumer the opportunity of optimizing costs and investments with respect to different retrofitting options to facilitate early decision making in the planning phase. Chidiac et al. [32] developed a screening methodology for office buildings regarding what retrofitting measures were the most cost-beneficial and energy efficient, using pay-back period as the economic measurement of beneficial alternatives. Papadopoulos et al. [33] touches the fact that the incentive for broad refurbishment in cities (Greek conditions) can be low when energy prices are low, but then when energy prices go up the costs of having aged and outdated buildings become evident, and the need for energy efficiency refurbishments can be high. The findings stress the fact that long-term perspectives can be beneficial when looking at LCC and energy savings in buildings.

Jakob [34] investigated the cost-benefits of insulation retrofitting measures, i.e. roof insulation, wall insulation, changing windows etc, and found that bettering insulation is a good and economically safe measure considering that energy prices often go up over time, and that insulation retrofitting measures have a long life-length of three to five decades. They noted that retrofitting also brings other co-benefits, (better indoor quality, better noise environment, raising market and rent value of the building etc), which mostly is overlooked positives of retrofitting measures. He recommends more attention being put to these benefits. Energy efficiency measures, specifically insulation measures, can be up to three times more expensive to do in a retrofitting way than applying them in the construction phase, making it important both financially and environmentally for stakeholders to be aware in their decision-making before raising a building [34]. LCA can be used to compare building scenarios and alternatives regarding design and material choice and can therefore be helpful in informative decision-making [7].

Further, Marszal et al. [35] compared LCC of on-site and off-site renewable energy generation in connection with a building, in order for the building to become a Net Zero Energy Building (Net ZEB). They found that for the on-site options it was most economic to go for maximum energy efficiency of the building, while for off-site generation the opposite was true and therefore in the off-site case the best economical alternative was to maximize renewable energy generation.

A concept encountered when investigating the relationship between user behavior, energy efficiency measures and cost-effectiveness is the *rebound effect*. Greening et al. [36] reviewed articles looking at the phenomenon. Rebound means that if energy efficiency measures are applied to a building, lowering its energy usage, the unit price for energy will decrease, giving the inhabitants less of an incentive to reduce/maintain the indoor temperature to recommended values, but instead raise the temperature and thereby increasing the energy use. This can therefore offset the energy efficiency measures initially applied. [36]. This is one reason that indicates the hardships of predicting life cycle costs for buildings since not only technical parameters are to be considered. Ortiz-Rodriguez [37] found that inequities in consumption habits affected energy consumption in two similar dwellings being situated in different countries, further strengthening the argument that socio-economical and cultural differences/habits affect the life cycle cost of buildings.

# 4 LCA challenges and solutions

On the topic of challenges with LCA, Sartori et al. [3] gives a good introduction to the area and discusses challenges with LCA and LCA in connection with environmental certification systems for buildings. Mentioned problems are that buildings have a long life-span, and therefore parameters change overtime- introducing uncertainties in the LCA result, highlighting the fact that the results of a LCA is a prediction of the probable environmental impact from a buildings' life-span on behalf of made assumptions and approximations. Choice of calculation tools and made approximations are parameters affecting LCA output, as well as the fact that different calculation tools provide different outputs depending on the calculation process of the software [3]. Transparency of the calculations and of the data in used databases is also a common problem. Parameters such as local weather, how the building is used and for what, material choices and production chains and cultural and social differences all affect the collective final environmental impact of buildings. Ways of weighting environmental impacts are a necessity in both LCA and GBRS, introducing a level of subjectivity for both systems, which problematizes comparisons [3]. Another flaw with LCA (compared with GBRS) is that it, by nature, provides output focused on environmental damage, whereas GBRS points to the environmental positives of a building, since a certified building has accomplished a certain standard allowing it to be certified. This leads to building companies using GBRS in marketing, while LCA can be perceived as somewhat negative. This fact that LCA focuses on the environmental burden emphasizes the advantages of integrating it during the design process- since it then can be used to lower environmental impacts. GBRS requires a building to be constructed before certification, taking away the possibility of using GBRS in the design process [3]. A challenge with LCA with potential for improvement is the fact that in the early design phase there is a lack of detailed knowledge of material data for the planned building [38]. Accordingly, LCAs are often conducted in late design phases and later, due to more knowledge of to-be-used materials later on in the design/construction phases. However, the later a LCA is conducted in the planning- and construction phase of a building, the smaller the window for informed decision making regarding measures to lower environmental impact becomes [38, 39].

Zabalza et al. [40] looked at motivators and inhibitors for conducting LCAs. Among the drivers listed were subsidies and loans for reducing environmental impacts, environmental labels for buildings, benefits in marketing, simplified data acquisition and environmental targets by nations and their building sectors. Among the barriers listed were prejudices about the accuracy of results, see also Malmqvist et al. [8]. Further, low demand and poor incentives for LCAs and lack of legal requirements for implementations of LCAs work as barriers hindering expansion of LCA, as well as discrepancies in results depending on calculation tool, hardships in understanding the results and how to apply them [40]. High costs and complicated calculation tools, lack of/poor knowledge regarding environmental impacts and the calculations of such impacts, poor cooperation between application/tool manufacturers and costumers/users, weak link with applications for energy certifications and a lack of standardization of program interfaces used in the building sector are also noted as barriers and challenges [40].

Nair et al. [38] conducted a survey among personnel working in consultancy companies, construction companies and municipalities regarding the newly implemented Swedish legislation on climate declarations for buildings. The climate declarations are based on LCA methodology and so several opinions regarding LCA challenges were aired by the respondents. Regarding LCA tools, the opinions were raised that some sort of standard should be required for the tools, and that the data in the tools should be quality assured with verified calculations methods [38]. Others suggest, though, that by not restricting the choice of tool the chances increased for finding optimized tools that suit specific projects the best on the quest for finding ways of lowering environmental impact [38]. Further problems aired were that there can be a lack of knowledge in how to properly conduct an LCA among building company personnel, and that they are deterred from it due to presumed complexity and time consumption of conducting such studies [38]. The lack of competence was emphasized by some of the respondents in the sense that some building company staff experienced uncertainty as for how to determine if a chosen consultant/company was competent enough to conduct the desired LCA [38].

Anand et al. [41] did a review of the research of the LCA area and found gaps, and therefore research opportunities, in the following areas: **functional unit**- with challenges being observed differences between actual environmental impact and calculated impact as well as the reliability of the calculated service life of buildings, **inventory analysis**- challenge being missing data, **system boundaries**- challenge being that there is no standardized procedure for defining the system boundaries, **impact assessment**- challenge being in how to accomplish comparisons of LCA results, and to make embodied energy an impact indicator, and **beyond LCA**- challenges being integrating results from LCA into certification systems and how to standardize/make a verification procedure for that process as well as looking at how deconstruction before the assumed building life time ends affects the environmental impact of the building.

## 4.1 LCIA methods

Säynäjoki et al. [11] explained in a review article the LCA area and methodically argued on behalf of studied literature regarding positives and negatives with the process-bases, I-O and hybrid approaches for LCIA. For the process-based approach they found it to be the most commonly used method for LCIA in the literature they studied [11]. In the process-based approach, environmental impacts are assessed according to energy and mass flows, process by process. This requires system boundaries to be set, which may lead to truncation errors due to some processes being excluded [11]. The I-O based approach originates from purchase-sales matrices from industries and uses the same thinking applied to the environmental impact. Truncation errors is not a problem here since transaction matrices describes how one monetary transaction in one sector can create another monetary transaction in another sector. On the other hand, aggregated errors arise due to emissions for one specific monetary transaction being comprised of weighted average of sectors included in that transaction [11]. Further issues with the I-O-based approach is that I-O tables often assume same production procedures for domestic and non-domestic production. Hybrid LCA is an approach aiming to take the positives of process-based and I-O approach and filling in the gaps in the respective method [11]. Subjectivity in establishing boundaries between the process based and I-O methods to establish the hybrid method leads to hardships and uncertainties in comparing results. 86 of the reviewed studies used process-based LCA, 19 with hybrid approach and 11 with the I-O approach [11].

## 4.2 Data/database issues

A problem described by the literature is deviations of data between databases [42]. Peereboom et al. [43] found that using different databases for the same LCA (on a PVC-material) lead to significantly differing results (0-100%) difference. Data on substances with high environmental impact, (whose emissions and following environmental impact were easier to measure) differed less than data on substances with lower environmental impact [43]. The effect was corresponding in the final LCA output. Air pollutant data differed less numerically than pollution types to soil or water, and were also more extensively reported. Emissions specific to processes also differed more [43]. Causes identified for differences in data were geographical reasons, differences in naming of pollutant/substance categories, system boundaries, differing usage of category definitions and substance categorization [43]. Takano et al. [44] investigated five LCA databases and the discrepancies in the values for certain materials used in three investigated buildings in Finland. Wooden products saw the biggest disparity and values for concrete showed low discrepancies. They also found that there was a significant difference in the amount of construction products available in the databases, leading to assumptions having to be made when using a similar material [44]. How data was allocated, (based on mass, economical value or volume) can also affect final GHG emissions from that product in the LCA. They recommended increased transparency regarding how the values for (GHG) emissions were retrieved originally, and to broaden the amount of data/choices for each material [44]. Also, they advise that rather than trying to unify LCA methodologies, which they argue will be hard due to discrepancies in databases regarding environmental burden of materials etc, to instead establish a communication- and reporting systems for LCA results, to facilitate comparisons of results and increase transparency [44]. Simpler information is preferable from the point of view of a designer, they argue, and since the discrepancies in databases can be explained by the large number of data elements, this also strengthens the argument for a communications and reporting system instead as it can be easier to develop and achieve [44]. Yokoo et al. [45] investigated the differences in embodied energy and embodied CO2 in buildings using three different databases. Depending on whether the building had a steel structure or a concrete structure the difference in embodied energy could be up to 16% and embodied CO2 could differ by 28% between databases [45]. The results were not discussed though.

Scheuer et al. [46] did a case study on a university building. They discussed the importance of initial design since that sets the benchmark for later on performance during the operational phase. The need for high quality data in initial stages are emphasized since that can reflect performance characteristics that are unusual [46]. They also call for in detail evaluations of building features early on in the design stage. The necessity of considering multiple scenarios for the building is noted, since parameters such as regulations, occupant behavior, equipment performance, renovations schedules etc affects the result in an LCA [46]. Demand (conservation and consumption behavior), performance (equipment installed and energy services) and material burdens (replacement schedules and choices of material) are the three most important parameters, they argue, when considering multiple future scenarios. To improve LCA, database improvement, higher data availability and impact categories that are better developed are requested [46].

Voices have been raised within the LCA scientific community proposing an establishment of a global database to homogenize the databases being basis for LCA practices [10, 11]. This to increase and homogenize data quality, quantity and detail. Frischknecht [47] wrote on the topic and presented the argument that there is a value in having a plurality in LCA methodology since ”it reflects plurality in society”, and that would therefore be an argument against homogenizing LCA databases and methodology too much, by for example establishing a global database [47].

Säynäjoki et al. [11] recommended a global database as a solution to better understand and decrease variations in LCA results. Bahramian et al. [10] called for open source databases and software to improve transparency and facilitate scientific and commercial collaboration and comparisons.

Uncertainty in results due to the quality of input data is a problem in LCA studies. Usage of generic data may induce uncertainties at the local level. Bahramian et al [10] suggested usage of more local data if there are uncertainties regarding relevance of results to the local level due to lack of local data in the LCA analysis. To derive and use local data can be more time-consuming though, they note [10]. Regarding uncertainties, they note that there are variations in the definitions of uncertainties, and relates that to lacks in the methodological descriptions in the ISO standards. Model, scenario, system boundaries and parameter uncertainties were the most commonly considered uncertainties in the literature [10].

To determine data quality, Nwodo et al. [7] requests usage of more EPD:s that can be verified. Thereby data quality will rise and so also the quality of the results, that will be easier to verify [7]. Dosshe et al. [42] discusses harmonization of EPD:s on regional level. That could decrease discrepancies of EPD:s and therefore in the input data of LCA. Further, Nwodo et al. [7] found proposals in the LCA research community for usage of statistical approaches for sensitivity/uncertainty analysis of LCA methodologies and results. Pannier et al. [48] conducted a comparative study of different methods for sensitivity analysis for LCA assessments, differing in how thorough and time-consuming they were. For example, Minimum-Maximum Sensitivity Analysis (MMSA) took four minutes whereas SRC and Sobol (both global sensitivity analysis methods) took 2 h 20 minutes and 180 hours respectively [48]. They found that the assessed methods for sensitivity analysis identified the same set of influential factors affecting sensitivity/uncertainty in the results. The main factors identified were electricity mix, life time of the building and factors having an effect on energy consumption in the building [48].

## 4.3 Why LCA results differ between studies

Results of LCA studies can vary significantly, both between individual studies but also within the same studies [11]. Säynäjoki et al. [11] exemplifies by presenting the lowest and highest found values in their review article being 0.025 and 2 tons of $CO2_e/m^2$. Those two specific studies used process-based and I-O approach respectively [11]. In all they investigated 116 cases from 47 scientific studies for their review article. For a concrete apartment building in a cold climate two similar studies reached 0.2 and 1.1 tons of $CO2_e/m^2$, and two similar brick-covered detached houses was found to have 0.26 and 1.01-1.17 tons of $CO2_e/m^2$ in two separate but similar studies. This illustrates LCA results variation of similar buildings but by separate studies [11]. Further on they looked at four parameters; building type, main material, case size and climate zone as possible explanations for results variation. By arguing that if the reviewed studies were comparable these four categories would explain the variations of LCA results, and also the variations in the results within those four categories (between studies) would not vary much. It turned out that no pattern could be identified for any of the investigated four categories and so it was concluded that these four categories, being connected to the physical building (contextual) could not be the explanation for the big variations in the results. One interesting finding was that detached buildings had higher average GHG emissions compared to office, apartment and public buildings, and Säynäjoki et al. argues that this might be due to detached buildings having more unique designs [11]. The difference could also be seen within buildings having the same classification. Variations and the widest range of results were found for residential buildings [11]. Since contextual reasons were rejected as an explanation for the variation in results of the reviewed studies they therefore investigated methodological differences as an explanation, looking at the four ISO 14040 main steps. A summary of their reasoning is provided below:

- Goal and Scope

  The scope of an LCA can impact the results because depending on how wide/narrow the scope is some building materials or processes/modules may be omitted. Säynäjoki et al. [11] claims that the studies with the narrowest scopes tend to place themselves in the lower end of their rank order of environmental impact. For example, research is cited that has found construction site emissions to constitute 3-15% of final environmental impact [11], impact that would not be accounted for if the construction site is omitted, as was done in [40, 49]. This phenomenon of having to set boundaries for the analysis and therefore possibly exclude significant processes is called *truncation error* [11]. Since I-O approaches and hybrid approaches do not require the same limitations they can suffer from aggregation errors, in which the same process may be included more than once, see Section 4.1. Out of the analyzed studies in Säynäjoki et al. [11] the average emissions from 86 process-based studies was 0.31 tons of $CO2e/m^2$, whereas average for 19 analyzed hybrid based and 11 I-O based studies was 0.58 $CO2e/m^2$ and 1.15 $CO2e/m^2$ respectively, giving a brief illustration that the approach for LCI and LCIA may affect the final output [11]. An article was cited that had doubled a buildings impact using the same scope but switching from process-based to hybrid LCA approach. An important feature to consider is how building materials may work as carbon sinks, with wood commonly considered to work as a carbon sink [11]. Considering wood as carbon sink can also be complex when the wood is used as building material, since consideration have to be taken of how the deforested land is re-forested again [11].

- LCI

  Although the ISO 14040 standard describes how the LCI shall be conducted, still this step is often briefly described in the methods of many studies- making comparisons of LCA studies tricky due to lack of insight in the actual LCI step [11]. Here the truncation error can be hard to approximate if the study is not transparent about what products and production chain steps are included and excluded [11]. The truncation error of an Australian industry sector, using a simplified process-based approach, was found to be roughly 50% when only considering direct energy consumption, and over 30% when additional secondary paths of input were considered [11]. Input data quality is often a problem since initially in the construction/design process material quantities are estimations of what later actually turns out to be needed [11]. Input data problems are also discussed in [3, 43, 44, 45], and simplifications regarding data and data acquisition and their implications on results are discussed in [46, 50, 51].

- LCIA

  Using an I-O approach for the LCIA, the three main error sources mentioned are; proportionality errors, errors from homogeneity assumption and aggregation errors. Proportionality errors implies assumptions of linear relationship between price and environmental impact of a sector/product [11]. Homogeneity issues are due to assumptions that environmental impact is the same per monetary transaction for products in an I-O sector [11]. Aggregation errors arises because I-O models for different areas are fused into one model. Process-based approaches suffer from similar aggregation/average problems as the I-O approach in the sense that material data in tools and databases can be generic data consisting of average data of the material from several countries [11]. For all three approaches technological development and temporal changes of fuel in production of materials leads to material data quickly being outdated and therefore less accurate [11].

- Results interpretation and presentation

  As for how result reporting affects comparability they reason that level of detail in result presentation affects the possibility to scrutinize the quality of the results. As mentioned earlier a common problem encountered was that that scope and method are poorly explained, making comparisons hard as it is tricky to navigate through practitioners' assumptions and assess their validness if they are not clearly presented. Increased transparency and thoroughness in scope and method presentation, to make contributions of subjective assumption/choices clearer are advised as a conclusion [11].

Further examples of how LCA results can differ are presented by Bahramian et al. [10]. In a review article they looked at the LCA research area from 1995-2018 by studying roughly 230 research studies. Average share of embodied and operational energy out of the life cycle energy was 39% and 62% respectively in the research articles. Big regional differences were observed when the research articles' results were sorted by the geographical regions of Europe, Americas, Oceania and Asia, with share of embodied energy of life cycle energy then being (36.22%, 56.95%, 20.8% and 34.68%). Calculation method and subjectivity in system boundary selection were presented as the biggest reasons for the observed results variation [10].

### 4.4 Comparability issues

Buyle et al. [4] conducted a review of the literature in the LCA area and found in it some of the problems mentioned in [3, 8, 38, 52] that comparability between LCA studies can be compromised due to climatic differences between studies and/or between the investigated building and the climatic reference in the calculation tool/database and that local regulations, comfort requirements, methodological differences can make comparisons tricky to conduct. Further problems noted were hardships of knowing the building life span- leading to estimations having to be made in that area, thereby uncertainties are induced to the LCA result. They propose that calculating environmental impact in the unit of $[\frac{burden}{m^2 useful floorarea}]$ or $[\frac{burden}{person}]$ can overcome problems with compromised comparability regarding the above mentioned differences in LCA studies [4]. They note that elements like system boundaries, level of detail and assumptions still can differ, and that LCAs are a simplified model of reality and so this by itself induces uncertainties for the parameters, the model and the life scenario of the building [4], see also Sartori et al. [3]. Buyle et al. [4] note that this latter problem can be analyzed statistically if quality indicators for data on processes and materials exist in the database of choice. Ecoinvent, they note, provides this type of quality indicators. The reliability of the LCA output is enhanced by this scrutiny of variability and stochastic error of the results. A language based on probability is recommended for results communication to emphasize the predictive nature of LCA [4]. As an explanation why head- to head results comparison between studies are hard to make, Bahramian et al. [10] lists building typology, site-specific characteristics, indoor decoration and maintenance quality and energy efficient appliances as obstructing categories. To ease comparison between LCC and LCA, Nwodo et al. [7] suggests to unify the units of LCC, LCA for results-reporting, suggesting for example MJ/unit area or per occupant as results unit, saying that such a unit could be transformed to unit currency for the LCC case.

#### 4.4.1 Life-span

What life-span that is chosen for an LCA analysis affects how and in what way it is comparable to others. Bahramian et al. [10] found a range of 20 to more than 100 years used as life-span for LCA analyses in their review of some 230 studies carried out between 1995-2018. Uncertainty in operational energy share of total lifetime energy is big for buildings with longer life-spans they noted [10]. Nwodo et al. [7] proposed to use a scientific basis for establishing the life-span of the building being investigated instead of using ”common-pratice” life-spans. Scheuer et al [46] listed the life-span of all components included in the building LCA analysis they conducted to establish the analysis life-span, going with the life-span of the longest lasting component as the analysis life-span [46]. Uncertainty in life-span of a building is inevitable, but the calculated environmental impact depends on the building being used as predicted and that components and the building are not replaced, changed or demolished before the, for the calculations used, lifespan ends. However, Aikivuori [53] found that subjective opinions of the decision maker accounted for 44 % of refurbishment initiations, changes in usage purpose of the building for 26%, whereas failure due to deterioration was the reason for initiated refurbishment in only 17 % of the studied refurbishments. He showed thereby that refurbishments are often initiated by other reasons than functional, making predictions of the life-span of a building hard- which can induce uncertainties in the results. It shall be noted that Aikivuori’s article [53] is from 1999 and the situation may be different now. Future-wise, developing some kind of benchmarks for establishing life-span usage in LCA may facilitate LCA study comparison.

#### 4.4.2 Functional Unit

The functional unit in LCA studies is important since LCI inputs and outputs in the LCIA relates to the functional unit [7]. Even though ISO 14040 and EN15978 addresses functional unit definition, there are variations in the literature in how functional unit is defined and presented [7]. Functional unit is related to how the results can be presented and therefore for results’ comparability. As a minimum, Nwodo et al. [7] suggests that functional unit definition should include; type of building, functional and technical requirements of the building (e.g. energy performance), required service life and pattern of usage.

#### 4.4.3 Subjectivity in weighting factors

Another problem that affects LCA results and thereby comparability is, by the LCA practitioner, induced subjectivity in the weighting factors used for calculating the impacts in the different impact categories [42]. The imposed subjectivity affects fairness in comparisons of LCA studies from different regions and countries due to the people creating the weighting factors often basing their weighting factors on their own knowledge, which would be affected by local and regional conditions. Nwodo et al. [7] also addresses the topic and notes that voices in the research community have suggested using exergy as an impact indicator.

#### 4.4.4 Benchmarks

Benchmarks can be a way to set results in perspective and rank buildings with regard to their environmental impact. Minunno et al. [54] did a meta-analysis and systematic literature review of the LCA research area and developed material benchmarks that LCA practitioners can use. Their main focus were on concrete, steel and timber. The benchmark was designed for 5 categories, making results relate to a box plot model involving the results collected in their literature review. Suggested improvements were then also presented as well as how much these improvements affects embodied carbon and energy. Five improvement categories were developed, among the most efficient were timber instead of concrete (43% lower embodied energy and 68% lower embodied carbon), recycle steel (40-45% decrease in embodied energy and up to 60% for embodied carbon), by-product integration in concrete (using 75% slag integration lead to 66% lower embodied carbon) [54]. They also found that shipping versus road transport was an efficient measure to decrease transportation impact, with shipping leading to 8% of embodied energy and 26% of embodied carbon compared to road transport of the same amount of construction material [54]. To construct products for disassembly and reusage was the last proposed improvement to lower embodied energy and carbon [54]. These two steps of results ranking and improvement proposal were suggested to be integrated into the four step ISO 14040 standard for LCA practicing. Also they showed that choice of functional unit can be important in understanding the impact of materials, for example using MJ/kg for embodied energy and kgCO2eq/kg for embodied carbon, the impact ratio of timber vs concrete was 727% and 236%, whereas using kJ/kNm for embodied energy and CO2eq/kNm for embodied carbon the ratio changed to 54% and 17%, (percentages based on numbers presented in their article) [54]. And so functional unit is important to carefully consider to understand environmental impact in LCA. Their investigation was limited to the study of materials for buildings. Operational energy and water were omitted [54]. Schlegl et al. [55] looked at how integration of LCA benchmarks into early planning phases of buildings can be a measure for reducing a buildings environmental impact and resource consumption. They used a particular database as the basis for their analysis and evaluated the certified buildings in the database according to environmental indicators of different life cycles, which thereafter could work as benchmarks for new buildings. They noted that level of detail on the data, and deviation of structure in data made it hard to develop automatically calculated and general benchmarks. Dosshe et al. [42] concluded from their review of LCA literature that benchmark development as of up until now mostly have been addressed on a national basis.

## 4.5 Simplification of LCA procedure as solution to complexity issues

Due to the extensiveness of LCA practicing, simplifications of the included modules and the practicing/calculation process is a way of increasing LCA usage and a solution to issues with complexity. Malmqvist et al. [8] suggests, in order to simplify the LCA methodology, to focus on (1) larger elements of the building to simplify data acquisition, (2) to use generic data on emissions, omit end of life phases and transportation and to instead focus on the most important substances contributing to environmental impact categories in order to make the inventory phase simpler, (3) focusing on a just a few categories of impact to simplify calculations and (4) by using improved applications of CAD/BIM models integrated into LCA calculation tools the work time can be reduced and acquisition of building data can be facilitated. Zabalza et al. [40] omitted end of life stages, maintenance, repair and replacement (MRR) and the construction process stage including its transportation element in the LCA study. The same phases ((A4,A5), B1-B5, B7, EoL (C) and D)) were also omitted by Karami et al. [49].

Bahramian et al. [10] found the most common simplifications of LCA methodologies from 19952018 to be the omittance of different EN15978 phases. B3 and B5 were commonly overlooked. Commonly considered phases were A3-A5 (in more than 70% of studies), B1, B2 B4 were considered by 57% of studies. In 63% of the reviewed studies B6 and B7 were considered, 54% considered C1-4 and only 11% considered D [10]. Initial embodied energy was often neglected in favor of recurrent embodied energy (maintenance etc) and demolition energy. Since operational energy have been extensively studied, initial embodied energy is a coming important area of research the authors claim [10].

Continuing on the theme of simplifying LCA conductance, Kellenberger & Althaus [56] examined how omitting certain ancillary materials and processes affected the final LCA output and compared that to an LCA in which those materials and processes were included. They found that omitting transports and ancillary materials had an impact on final result, whereas omitting waste cutting and the building process were insignificant to the final LCA result. The all-inclusive vs fully reduced versions of the LCA differed by 15-30 % in the final impact. The research shows that simplifications regarding what materials and processes are included can have a significant impact on the final result, but that it is hard to draw general conclusions regarding how omitting a specific process/material component will affect final LCA result. An example, they state, is that impact from transportation and material increases with increased transportation distance and weight of materials transported [56].

Verdaguer et al. [50] conducted a review of 20 articles about LCA for single-family houses. It was concluded that in the reviewed research the focus of the simplifications was on definitions of system boundaries, the model, stages of the life cycle, building life scenarios, use generic sources for data or use databases, reduce number of environmental indicators, optimize the process for collection of data, functional unit reduction and how the result is communicated [50]. They noted that while making simplifications it is important to have a thorough understanding of the implications this might have on the final result. The simplification strategies made the LCAs easier to conduct by accomplishing data reduction, making calculations of processes and environmental impacts less complex [50]. All simplifications had in common that they related to the objective and scope of the LCA study. The comparability of the LCA results, though, can be compromised due to heterogeneity of the simplifications applied. The authors therefore present a number of recommendations when simplifying LCA studies:

- EN15978 has improved communication of LCA results. Common criteria for result comparison are advised to be developed in the area of partial application of LCA on buildings and similar building typologies. Suggestions are for example to present results by building system or building component, e.g. roof, windows, envelope of building etc. Comparison of environmental impact, organized by component or life cycle stage, would thereby be facilitated [50]
- Common criteria regarding definitions of transportation, construction, use phase, MRR, EoL, refurbishment and characteristics that are specific for the region of the building are advised to be developed for improved comparison possibilities [50]
- Continuous development of EPD:s, especially in the case of single-family buildings, is advised, since usage of EPD is a commonly encountered simplification in the product/material stages/modules [50]

### 4.5.1 LCA and BIM software integration

Verdaguer et al. [50] also mentions integration of LCA softwares with BIM softwares as a solution to simplify LCA conductance, making data acquisition and allocation easier, better structured and less time-consuming. Sartori et al. [3] also advised inclusion of BIM models into calculations tools as a way of making LCA an integrated part of building designs instead of a parallel process. Basbagill et al. [57] developed an integrated method between Building Information Model (BIM), Maintenance, Repair and Replacement schedule (MRR), sensitivity analysis, energy simulations and LCA to make early decision-making easier with the purpose of reduced embodied GHG emissions. They demonstrated their method on a specific building and showed that, regarding material choices, the elements affecting embodied environmental impact the most were in cladding materials, substructure, interiors and shell, whereas service equipment, doors and stairs had the smallest embodied environmental impact [57]. They recommended their method to be applied to more buildings since their results were from application on a particular building. Their work showed that by integrating BIM, energy simulation, sensitivity analysis and MRR schedules, early decision making to reduce embodied GHG emissions can be simplified and made clearer. Nwodo et al. [7] concluded from their literature review that integrating BIM models and LCA tools decreases data intensity and time-consumption. Tally (an LCA tool) can be used in AutoDesk Revit (a BIM software) as a plug-in. Challenges with BIM-LCA software integration are that still there exists compatibility issues (interoperability issues) between LCA tools and BIM model softwares, and BIM models are often not fully developed early on in building projects when LCA can be the most effective for informed decision making to lower environmental impacts [7]

## 4.6 Mention-worthy

Jönsson [51] compared six approaches for assessing environmental impact of building products, and extrapolated over advantages and disadvantages with high transparency, comprehensiveness of results, limitations with too much standardization and possible limitations with using too specific data. Main reasoning were that too high requirements for transparency may cause limitations in applicability of results due to possibility of producers wanting to keep some data confidential [51]. Making the result too comprehensive and cutting out interpretation of the result may lead to hardships for costumers to understand the results, with the contrary being that a result with too much aggregation and interpretation makes it hard to understand underlying assumptions [51]. Too much standardization of procedures can lead to low flexibility, whereas too low standardization can make results less trustworthy/have lower relevance [51]. Too detailed data may lead to the result being specific to the conditions of that case, whereas using mainly generic data may lead to the usefulness of the result going down [51]. The article is from the year 2000 and so is relatively old as compared to recent research and reviews of the LCA area, see [4, 6, 7, 10, 11, 24, 41, 42, 50, 54, 58, 59].

Regarding LCA tools development, Hollberg et al. [60] proposes that it may be advantageous to involve target users in the development process of LCA tools. They interviewed target users about what is important for a calculation tool adapted for the new Swedish Climate Law [61] and then developed the tool and let the interviewees give feedback. The importance of fast and transparent calculations was emphasized by the target users, as well as transparency of calculations and connection to 3D-models (presumably BIM model integration). Inquiries that tools be adapted for local conditions were made [60].

Moreno et al. [39] investigated how LCA and Functional Analysis (FA) could be integrated to improve one another in a construction process. By looking at similarities and differences in certain steps for both processes it was found where the two concepts complemented each other and where the similarities already were big. Life cycle thinking, functional unit and life cycle inventory (LCI) were concepts from LCA that could benefit FA, and expression of need, function and functional requirements were concepts from FA that could benefit LCA [39].

## 4.7 Future research topics

### 4.7.1 Impact categories extension

LCA can be used to assess impact categories that are not only connected to the environment. Nwodo et al. listed some examples from their review of the LCA literature, being indoor air quality, water consumption, rebound effect, aging, biogenic carbon emissions, impact of pollutants from materials on human health, toxicity, land use and changes in building usage [7]. Reasons for these impact categories seldom being investigated could be low awareness of them and disputing opinions regarding how to properly assess them [7]. These impact categories are possible topics for future LCA research and can, if more frequently assessed, lead to wider usage of LCA.

#### 4.7.2 Dynamic LCA

The LCA practicing up until today has mostly been a static approach. However, consideration of time variations of parameters such as weighting factors, occupant behavior and technological development/progress is an area with potential for improvement. This is called *Dynamic LCA* [7]. There are not many studies on the area as of right now. Inhibitors to the development of dynamic LCA practicing are low spatial availability, shortage of data that makes time variability possible to account for, uncertainty of future scenarios and how to characterize dynamic LCA methods [7]. A dynamic LCA approach could contribute to better accuracy of LCA results with respect to spatial and temporal variations, but would however still be a prediction [7].

#### 4.7.3 Mobility patterns in neighborhood LCA

The purpose of this section is to present recent research on the topic of mobility patterns within neighborhood LCA. Neighborhood LCA can be viewed as a form of Dynamic LCA and the perspective of the LCA is widened from the building level to neighborhood level. Processes connected to neighborhoods and residential areas can be evaluated, and research have been produced on the area in the last decade [62, 63]. The role of mobility patterns in neighborhood LCA has gained interest in recent years [62]. In an attempt to assess the impact that transportation connected to the inhabitants of a neighborhood has on the total life cycle impact from the neighborhood, Allende and Stephan [64] investigated the life cycle impact of transportation connected to a newly developed neighborhood (with a sustainable profile) in Melbourne, Australia. They compared several scenarios to a business as usual scenario, investigating how decreases in steps of 25% in the private car transportation distance affected energy requirements and GHG emissions in the neighborhood. Findings were that for every 25% decrease in private car transportation distance the life cycle transportation GHG emissions decreased by 15% [64]. The reductions in private car transportation distance was assumed to be divided equally between public transport and active transport (walking, using bicycle etc). Baselines from Moreland City Council were used to model transportation impact [64]. For the 75% private car distance cut case, the share of life cycle energy was 32%, 34%, 34% respectively for embodied energy, operational energy and transportation energy. However, looking at life cycle GHG emissions, the share changed to 37%, 4%, 59% respectively. They used an electricity alternative with 91% hydropower in the electricity mix for the green 75% private car reduction scenario. Indirect requirements were the main culprit for transportation GHG emissions [64]. Highlighted by the authors is the fact that when looking at LCA on a neighborhood scale, the importance of energy source is big, and with cars being increasingly electrified indirect impacts of electricity generation is important to consider to get a representative result. In a similar study of a Melbourne suburban neighborhood, Stephan et al. [65] found that transportation accounted for 33.6% and 36% of the life cycle energy and life cycle GHG emissions respectively. The share of total transportation life cycle energy and life cycle GHG emissions between direct and indirect transportation requirements were roughly 50/50 [65]. Direct transportation requirements are from fuel consumption for vehicle propulsion, whereas indirect are from road building and maintenance, vehicle production etc [65]. An interesting finding was that indirect transportation requirements amounted to 123%

of direct primary heating demand, which in turn corresponded to 31.2% of total life-cycle operational energy and 27.6% of total life cycle operational GHG emissions [65]. This signals the big impact transportation, both indirectly and directly, has on a neighborhood level.

More studies of the area are Bastos et al. [66], that found that transportation accounted for 57% of life cycle non-renewable energy and 51% of life cycle GHG emissions for a suburban house, (about 20 km from city center). The case study compared a city-apartment case with a suburban house case in Lisbon, Portugal. The occupant transportation made the suburban case almost twice as energy (non-renewable) and carbon (GHG) intense, as compared to a city-apartment case. When transportation was omitted, the suburban case was around 9% more intense for non-renewable energy and GHG emissions [66]. Nichols et al. [67] investigated four neighborhoods in Austin, Texas and found that fuel consumption from private transport and embodied energy in the infrastructure (parking lots, roads, sideways, driveways etc.) accounted for 40-46% of total life cycle energy. Investigating life cycle impact of common housing types for Munich city center, city periphery and outside districts, Anderson et al. [68] found emissions to be 2.25 tons of $CO2_e/capita \cdot yr$, 2.74 $CO2_e/capita \cdot yr$, 3.32 $CO2_e/capita \cdot yr$ for city, periphery and outside district respectively for common housing types in the respective urban areas. Out of this, transportation and embodied energy in the mobility category (in vehicles and the infrastructure) accounted for 51.5%, 50.1% and 46.5% of the share of total emissions for respective urban region. After renovations of the investigated housing objects, the transportation share increased to 53.9%, 52.7% and 50.6% respectively [68]. This indicates that when considering overall emission reductions on a neighborhood scale, transportation issues becomes relatively more important to consider as energy efficiency renovations are carried out of the buildings, and it is conceivable that situations may appear when it can be more efficient regarding cutting GHG emissions to improve green transportation possibilities for neighborhood inhabitants than to renovate buildings.

Interesting comparative findings were made by Lausselet et al. [69] that investigated GHG emissions from Zero Village Bergen, a Zero Emissions Neighborhood pilot project by the ZEN Centre in Norway. Modules A1-3, B4 and B6 were investigated on a neighborhood level, including the neighborhood elements of mobility, buildings, networks, on-site energy infrastructure and open spaces. The results were that the mobility element (including both direct and indirect impacts from vehicle production and replacement, roads etc) constituted 40% of total neighborhood emissions, out of which 37% were from direct mobility (fuel consumption in vehicles etc). Lausselet et al. [69] changed their system boundaries to those of Bastos et al. [66] and found that using Bastos et al:s system boundaries lead to transportation constituting only 22% of life cycle GHG emissions. When Lausselet et al. [69] used system boundaries by Anderson et al. [68], they had the same result as [68] for product stage for vehicles- constituting 27% of life-cycle GHG emissions. This they noted, might be a coincidence since Anderson et al. [68] reported the majority of mobility emissions originating from operational phase, whereas Lausselet et al. [69] reached the opposite result. Lausselet et al. [69] explain the differences in results between their own study and the trial with Bastos et al. [66] system boundaries by possibly optimistic predictions of future share of electrical vehicles and an electricity mix with low emission intensity [69], since Bastos et al. [66] case study is in Lisbon, Portugal and Lausselet et al. [69] was carried out in Bergen, Norway. Yet another difference is that [66, 68] only investigate individual housings (but including mobility element) whereas [69] calculates for the neighborhood scale. This might also complicate comparison.

# 5 Climate declaration law: Sweden and Finland

On January 1st 2022 a new climate law came into action in Sweden. The law requires a climate declaration when new buildings are to be constructed. This is in line with the work of the Swedish authorities to decrease the climate impact from construction of new buildings. Four important modules that the SNBHBP worked on during the preparations of the law were to (1) develop an open database with data aimed to work as a basis for LCA calculations for the climate declarations [70]. The database shall include both generic product data to be used in initial phases of climate declarations if specific product data is still unknown (this can later be updated with EPD:s) and include scenarios for repairing, maintenance and refurbishment and EoL scenarios of the listed products. This is to facilitate and also homogenize climate declaration conductance. It is important that it is clear in the calculations where generic product data from the database have been use and when specific product data from EPD:s have been used. The database will be continuously updated for a 2027 law update, in collaboration with the climate register described hereafter [71, 72]. (2) Develop a climate register that can be used when the law is implemented [70]. The purpose of the register is to facilitate digital information exchange and to be part of the basis for developing references to define limit values for 2027 law update. The SNBHBP will be verifying the calculations in the registered climate declarations to develop a baseline for 2027 limit values. The register at the SNBHBP will be the collector of climate declarations and municipalities will then be able to verify from the register that the climate declaration for a planned building have been conducted and registered. It will be a way for centralized information exchange [70, 71, 72]. (3) Develop material for guidance and information [70] and (4) plan for continued developments of the law and how to eventually include the whole life cycle of the building in the climate declarations [70]. The purpose of the law is to increase the knowledge of LCA, decrease climate impact from construction of new buildings, raise stakeholder awareness of what they can contribute with in order to decrease climate impact of their business and raise general awareness of the climate impact by the building sector. During the planning/initiating phase of the climate law, an initiative was started to harmonize the building codes in the Nordic countries regarding climate impact. A symposium on the topic was arranged by the Finnish Ministry of Environment and the SNBHBP, named Nordic Climate Forum for Construction, held in Malmö, Sweden the 3rd of October 2019 [73]. The collaboration with Finland was/is particularly close, especially regarding the development of the climate data base and the method/requirements for the climate declarations [71, 72].

Initially, in Sweden, the climate declaration will only include the construction phases (A1-A5 in EN15978), and in later evaluations/implementations of the law the use phase (B in EN15978) will be implemented the energy declarations of buildings, required since 2006 within the law 2066:985 could be relevant to use within the extended climate declaration of buildings. The reason that only A1-A5 initially are included in the climate declaration is that the legislation is intended to lead to decreases in GHG emissions occurring today and that those modules are easy to verify [71, 72]. A problem with including operational phases (B) and EoL phases (C) is the risk of hardships in verifying the calculations, as the climate impact from construction can be verified whereas climate impact from operational and EoL phases includes assumptions and parameters with uncertainties for the building life scenarios. By not including B and C from EN15978 the SNBHBP aims to avoid the risk of building companies making the argument that their building will comply with emission regulations/targets overtime, instead of immediately leading to GHG emission decreases [71, 72]. On the other hand, the argument is also raised to include B6 in limit values for 2027 revision since A1-A3 along with B6 are the modules of the life-cycle of a building that causes the most GHG emissions [71, 72]. Continuing the argumentation, the SNBHBP adds that since phase B and C requires assumptions, a level of subjectivity is inserted into the parts of an LCA that includes B and C, and so they argue that including those phases will not necessarily lead to increased measures for decreasing GHG emissions in the construction sector. Assumptions in phases B and C regarding scenarios and EoL conductance therefore needs to follow some sort of standardization to minimize risks that buildings will meet climate goals simply because of subjective assumptions [71, 72]. The importance of verification and minimizing influence of subjective assumptions on the final result is also mentioned in [3, 11, 38, 41, 42, 58, 59], and so the SNBHBP argumentation can be anchored in the literature.

As of right now, there are no limit values for the GHG emissions from the required declared modules A1-A5 for new buildings. From 2027, it is proposed that limit values are introduced, and that they are set between 15-30% lower than a benchmark calculated from the registered climate declarations during the period from 1st of Jan 2022 to 2027 [71, 72]. From thereon the proposal is to have a linear decrease of the limit values with threshold of 40% decrease by 2035 and 80% decrease by 2043, as compared to the 2022-2027 benchmark value [71, 72]. Continued evaluations of limit values and how they affect the construction sector shall be conducted, so that the legislation does not drive any undesirable development for the sector. Until 2027, only A1-A5 are included in the legislation, but from 2027 it is proposed that also B2, B4, B6, C1-C4 and biogenic/technical carbon and net export of locally produced electricity are included in the climate declaration requirements [71, 72]. These proposed additional modules from EN15978 are also included in similar methods in other European and Nordic countries according to SNBHBP [72]. Also, no particular life-span for the climate declaration will be required until 2027, when a required 50 years will be the basis for the LCA analysis. Furthermore, some more building elements will have to be included in the climate declaration by 2027 as compared to now, when there is only a requirement for load-bearing structures, building envelope and interior walls to be considered [72]. In the case of, by the SNBHBP detected, significant deviations between the, by the builder, produced climate declaration an the, by the SNBHBP, controlled calculations, a sanction fee may be imposed on the building company/building developer if they cannot provide an explanation for the deviation within an agreed time-frame. SNBHBP uses the term ”materially deviation” but gives no details on specific numbers that would signify a materially deviation. A thorough framework for the law provided by the SNBHBP during the preparations for the climate law can be found in [72].

In a new assignment from Swedish government the SNBHBP is going to investigate how limit values can be legislated before 2027, and if refurbishments and reconstructions can be included in the now legislated climate declaration. The last date for the presentation of the investigation on May 15th 2023 [74].

According to the SNBHBP, the new law will have the following implications for building developers in Sweden: (1) A climate declaration, according to the by law decided requirements, needs to be conducted before construction of certain new buildings (2) If the climate declaration is required for the particular building it shall be handed in to the SNBHBP (3) When the climate declaration has been handed in a confirmation of the reception of the climate declaration is handed to the builder (4) To receive a clearance to proceed with the construction the building developer must hand in the confirmation to the Building Committee responsible for approving construction of new buildings [75]. For the Building Committees the law, according to the SNBHBP, will have the following implications [75]: • The Building Committee shall consider if the building that is filed for construction is required to be climate declared • During the technical consultation the Building Committee shall clarify the requirements of the climate declaration

- In the legal decision it can be appropriate to provide general information regarding the requirement of a climate declaration
- From the clearance for go-ahead with the construction it shall be made clear that a confirmation that a climate declaration of the building has been made is a document that should be provided to the Building Committee to get the final go-ahead
- Before the final go-ahead with construction the Building Committee shall make sure that a confirmation has been handed in to the Committee that a climate declaration of the building has been made
- At the final summit the Building Committee shall look at the conditions for a final go-ahead for the building. If the building is required to have a climate declaration it shall be addressed during the final consideration of the construction plans
- If a climate declaration has not been handed in to the Building Committee, a preliminary go-ahead can be issued pending that the building developer hands in a climate declaration within a known time-frame
- The Building Committee shall not, by itself, retrieve the confirmation of a finalized climate declaration for the building from the SNBHBP register. Neither shall the Committee wait for the quality control of the declaration or have to consider if the climate declaration is valid for all required contents
- When a final confirmation has been handed in to the Building Committee the Committee can give a final go-ahead

Some buildings and circumstances are exempt from the requirements of climate declaration before go-ahead for construction. Reconstructions, moving and refurbishment of buildings erected before 1st Jan 2022 are exempt from the new law. The same is for industry-buildings, buildings that have a gross area of less than 100 $m^2$, buildings that are used by the Swedish military and defence and buildings erected by private people that are not for business use. If the building has a limited (in time) building permit and the planned usage time is a maximum two years it is also exempt from a required climate declaration [76]. For the specifics of the law and the exact formulations, see also [76].

In the final Manual for Climate Declaration [61], provided by the SNBHBP, the specifics of the law, the climate database, the climate declaration register and how to climate declare can be found. How to present the climate impact for the EN15978 modules A1-A5, that are the modules included in the law as of right now, can also be found there. The SNBHBP advises the building developer to work continuously with the climate declaration during the planning and design phase of the building project since the possibilities for informed decisions to decrease climate impact are the biggest in those phases. Regarding when it is appropriate to register the climate declaration, the SNBHBP is not more specific than for the developer to do it at a ”time when the climate declaration represents the finalized building”. Since the climate declaration is required for the final go-ahead, a developer cannot start with the construction until a registered climate declaration can be found in the SNBHBP register [61]. Since the building developer is responsible for the climate declaration, SNBHBP advises for a developer to have a continuous dialogue with the party responsible for conducting the climate declaration, (be it an entrepreneur or consultant) regarding the requirements for the declaration [61]. Those requirements are for example how data is collected and how it shall be reported, how the data shall be saved (the building developer must save the declaration for 5 years according to the law), how the declaration work can/will be integrated into the planning/design process and how the declaration work will be continuously worked on, ways for communication etc [61]. The SNBHBP explains that the building developer may delegate parts of or the whole job with the climate declaration to other parties such as entrepreneurs and consultancy firms, but stresses the fact that the formal responsibility lays with the building developer to finalize a climate declaration within the requirements [77].

Regarding the time and finance needed for a climate declaration according to the new Swedish standard from Jan 1st 2022, Nordbro, a business legal firm, approximates time-consumption to be 120-241 hours with a cost of 98 000-241 000 SEK [78]. The Swedish Environmental Institute IVL provides calculations tools that can be used for climate declarations. The cost for using the tools depends on the thoroughness the customer demands. The basic tool costs 59 000 SEK before taxes, the extended version 90 000 SEK before taxes and a quality check of the calculations by an independent expert at IVL costs 9 900 SEK before taxes (per investigated project) [79]. Another tool for collecting material data and EPD:s in a structured way and connecting it to the design model of the building. Bimeye with Interaxo, provided by Tribia Addnote Group helps with gathering and sorting material data by synchronizing with the building model. The software then let's the user export the data to an LCA calculation tool of choice. No cost-information is provided openly on the website [80].

Finland is taking another approach in their development of statutory climate declaration. Their implementation and planning of a law on climate declaration are being done in conjunction with a total reform of their laws on land usage and building constructions [ 72, 81]. Finland has been developing a roadmap for their implementation since 2016, and have had drafts of the law on referral rounds. 2019-2020 they had a trial period for the climate declaration method applied to 40 buildings. After that a new referral round was being held [81], leading up to the current draft for the method to climate declare and the current ordinance [82, 83], both can be downloaded from [81]. The plan is to have the law enter into force by 2025 at last [84].

There are several differences between the Finnish and Swedish work with the climate declaration laws and the roadmaps for implementation. For the planning of the law Finland will implement it with limit values directly, last by the year 2025, but instead they have had the full-scale proposal for the law and climate declaration method on referral rounds for a longer period, starting from 2016 [81, 85]. Finland will also include more modules from EN15978 directly when the law is implemented, namely (for new buildings) A1-5, B4, B6, C1-4 and D [82], as opposed to Sweden that will not have a similar full-scale version until 2027 [71,72]. Refurbishments of existing buildings will also require a climate declaration in Finland, in that case the declaration is being done in the same way as for a new building but with module B5 being the added construction [82]. Moreover, aside from the climate declaration of the climate impact the building has, Finland will also require a ”carbon handprint” to be calculated, comprising of avoidance of greenhouse gases had the building not been constructed. Examples of processes that can be included in these calculations are carbonization of CO2 into the concrete, re-use of construction material, renewable energy production added to the grid in conjunction with the building project and biogenic/technical carbon in construction products with long life-spans [82]. The carbon handprint would essentially represent module D in EN15978 [82]. The Finnish database on climate impact for construction materials and the developed calculation tool for the climate declarations can be found in [86] and [85] respectively.

# 6 Conclusions

The building LCA research area has grown ever more diverse since starting to expand in the 90's. From in the beginning focusing on the building level it has in recent years evolved to include whole neighborhoods in the analysis, with system boundaries including transportation and many indirect impacts. Even though standards like EN15978 and ISO 14040 are established to harmonize LCA methodology it is evident that loopholes exist in many areas, leaving the door open for interpretations. On behalf of the studied literature a few suggestions for future improvement of the LCA research area are presented below

- There is a lack of clear guidance in the ISO 14040 as for how to define and establish uncertainties in LCA. It is suggested to review ISO 14040 guidance regarding uncertainties.

- In line with the expanding perspective from building level to neighborhood level, clear communication of scope, method and system boundaries is imperative. As exemplified by the differing results in neighborhood LCA research when repeating calculations using the method of one study but the boundaries of another- full transparency of scope, method and system boundaries are needed to understand varying results. To raise the quality of research and ability of comparisons, tt may be beneficial to give even more attention on communication of scope, method and system boundaries

- As the perspective in LCAs are being lifted to the neighborhood level it is important to communicate how direct and indirect impacts are accounted for and how they are allocated in the analysis. With simplifications in LCAs often being made by omitting certain processes, to communicate those simplifications using the EN15978 standard is advised. By doing so, included and excluded modules can be communicated in a distinct and harmonized way, facilitating for comparisons between studies and interpretation of the result relevance and robustness. References [40, 49, 69] are good examples of how module inclusion/exclusion can be communicated clearly using EN15978 standard.

Several studies mention benchmarks/registers/databases on both national and global scale. National databases already exist in some countries. To develop national registers of LCAs for comparison opportunities and development of national benchmarks is advised since the usefulness of having such established on a national level may be bigger than on a global level due the big differences in climate, building practices, production procedures, electricity/energy emission factors etc between countries. To administer benchmarks, databases and LCA registers on a national level is more manageable as well. Further, global scale databases may lead to data being too generic for the local level and the usefulness of a global database is then questionable. To establish benchmarks/registers by building type on a national level can also fill a purpose for comparability of LCA studies, enabling ranking of new buildings.

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[84] Finnish Ministry of Environment https://ym.fi/sv/byggande-och-markanvandning
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