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TOPICAL REVIEW

Can life-cycle assessment produce reliable policy guidelines in the building sector?

Antti Säynäjoki[1,2], **Jukka Heinonen**[1,3], **Seppo Junnila**[1] **and Arpad Horvath**[4]

[1] Aalto University, Department of Built Environment, P.O. Box 15800, 00076 Aalto, Finland
[2] University of California Berkeley, Berkeley Energy and Climate Institute, 450 Sutardja Dai Hall, CA 94720, Berkeley, California, USA
[3] University of Iceland, Faculty of Civil and Environmental Engineering, Hjardarhagi 2–6, 107 Reykjavik, Iceland
[4] University of California Berkeley, Department of Civil and Environmental Engineering, 215 McLaughlin Hall, CA 94720-1712, Berkeley, California, USA

E-mail: antti.saynajoki@aalto.fi

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Abstract

Life-cycle assessment (LCA) is an established methodology that can provide decision-makers with comprehensive data on the environmental impacts of products and processes during the entire life cycle. However, the literature on building LCAs consists of highly varying results between the studies, even when the assessed buildings are very similar. This makes it doubtful if LCA can actually produce reliable data for supporting policy-making in the building sector. However, no prior reviews looking into this issue in the building sector exist. This study includes an extensive literature review of LCA studies on the pre-use phase of buildings. The purpose of this study is to analyze the variation between the results of different studies and find out whether the differences can be explained by the contextual differences or if it is actually the methodological choices that cause the extremely high variation. We present 116 cases from 47 scientific articles and reports that used process LCA, input–output (IO) LCA or hybrid LCA to study the construction-phase GHG emissions of buildings. The results of the reviewed studies vary between 0.03 and 2.00 tons of GHG emissions per gross area. The lowest was assessed by process LCA and highest with IO LCA, and in general the lower end was found to be dominated by process LCA studies and the higher end by IO LCA studies, hybrid LCAs being placed in between. In general, it is the methodological issues and subjective choices of the LCA practitioner that cause the vast majority of the huge variance in the results. It thus seems that currently the published building LCAs do not offer solid background information for policy-making without deep understanding of the premises of a certain study and good methodological knowledge.

1. Introduction

Life-cycle assessment (LCA) is an established methodology that can provide decision-makers with comprehensive data on the environmental impacts of products and processes during the entire life cycle—from raw materials extraction to end-of-life treatment. It is intended to be a systematic, holistic, and objective method to evaluate the environmental burdens of a process or a product. Since the 1990s such frameworks as ISO 14040 (International Standard Organization 1997) and CEN/TC 350 (CEN/TC 350 Sustainability of construction works 2012), and, most recently, the EeBGuide InfoHub (Lasvaux *et al* 2014) have been developed to guide LCA practitioners towards standardized assessments.

Despite such development, several accepted ways of conducting an LCA have come about, and reasonably all can claim to give comprehensive results (Suh *et al* 2004). However, even though these should be compatible and comparable with each other, they can lead to different results due to the inherent differences in the approaches, the subjective and objective choices and assumptions an LCA practitioner can make during each stage of an assessment, and the availability of data. Multiple approaches and the abundance of choices for analysts could lead to results that are difficult to compare across studies or whose accuracy can be brought into question (Treloar *et al* 2001, Gustavsson *et al* 2006, Robertson *et al* 2012, Chau *et al* 2015).

The building and construction industry provides a useful example of an industry with an acute need for reliable and comparable information on a life cycle's environmental impacts in order to support decision making. The industry is credited with a major share of several environmental burdens. A specific feature of the industry is that many of its environmental burdens are either indirect (they occur in the supply chain) or are incurred during the long life cycle of the product. Legislative action is still under development. For example, the industry does not fall under the carbon credit scheme although some 30%–40% of global greenhouse gases (GHGs) are associated with the life-cycle emissions of buildings (Huovila *et al* 2007). Similarly, the supporting Energy Efficiency Directive (EED) of the European Commission mostly steers energy performance of the buildings (European Commission 2014). The GHGs from the manufacturing of materials, construction, and maintenance are not regulated, although they may be responsible for up to 50% of the life-cycle emissions (Junnila *et al* 2006, Blengini and Di Carlo 2010, Säynäjoki *et al* 2012).

In this study, we evaluate how coherent an understanding the scientific community has of the embodied energy (EE) and life-cycle GHG implications of buildings, as reflected in peer-reviewed literature and publicly available research reports. We concentrate on the construction or pre-use life-cycle stages as defined in the standard EN 15804 (U.S. Green Building Council 2012), including the five modules A1–A5: A1 'Raw material supply,' A2 'Processing phase transport,' A3 'Production of construction materials,' A4 'Transportation to the construction site,' and A5 'Construction site activities.' In the analysis particular emphasis is on methodological issues, but empirical implications are also studied. We present the results of over 100 cases of pre-use phase LCA studies and analyze them with regard to both the characteristics of the buildings and the LCA choices that might significantly affect the results. No such review exists despite the otherwise rich literature on EE and emissions. Building LCA reviews exist (e.g. Sharma *et al* 2011, Sartori and Hestnes 2007, Khasreen *et al* 2009, Chau *et al* 2015, Rossi *et al* 2012) but they concentrate on other aspects than the construction-phase emissions. With the analysis here we demonstrate how the methodological choices and assumptions seem to explain the huge variation in the published results, rather than building qualities or locations, which suggests an urgent need for further development in the field of assessment methods. Additionally, the details of the assessment process are often described in too little detail, which hinders transparency and the critical evaluation of the results.

We concentrate on GHGs and EE for two reasons. First, the literature on building LCAs is the richest on these two metrics (Khasreen *et al* 2009). Second, these two metrics are of very high current interest and have the potential to show how well environmental issues are analyzed in the state-of-the-art literature.

In section 2, the main approaches to LCAs are briefly summarized. Section 3 presents the research design, and section 4 summarizes and discusses the analysis results. Finally, the main conclusions are drawn in section 5.

2. LCA methods

There are two primary quantitative, methodical approaches to LCA: process LCA and input–output (IO) analysis-based LCA. Several combinations of the two, known as hybrid LCAs, have also emerged. The two main approaches have distinct features that can lead to different results even when the same case is concerned (e.g. Lenzen 2000, Junnila 2006, Liang and Zhang 2013).

Process LCA is the most established LCA application when determining the environmental impacts of a product or a process (Suh *et al* 2004, Junnila 2006). The emissions are assessed according to energy and mass flows, process by process. The method has all the characteristics to yield accurate results specific to a location and production conditions, but this approach inherently suffers from truncation error made in the selection of the system boundary within which the processes are included in the assessment (Suh *et al* 2004, Matthews *et al* 2008, Lenzen 2000). The cutoffs may introduce significant biases into the results since the impact of the excluded processes might not be known (Lenzen 2000).

IO LCAs do not suffer from truncation error as they are based on monetary sectoral transaction matrices that describe how a monetary transaction in one industry sector creates transactions in other sectors (Suh *et al* 2004, Hendrickson *et al* 2006), extended by various environmental emission vectors. As the transaction matrices are normally based on national IO accounts, the assessments are comprehensive in providing a full inventory of the emissions without boundary cutoffs. However, IO LCAs inherently suffer from several other problems. Even in the most disaggregated models each industry sector comprises many actual sectors with potentially different environmental impact profiles, and the emissions for a certain monetary transaction are a weighted average of all the comprised sectors (e.g., Crawford 2011). This is an aggregation error. Other known problems causing uncertainties are homogeneity and linearity assumptions (e.g. Treloar 1997, Crawford 2011). Finally, the assumption that imported goods are produced the same way as domestic goods is an inherent consequence of the domestic consumption basis of the majority of IO tables.

Hybrid LCAs are aimed at combining the positive features and reducing the negative features of the two basic approaches (Treloar *et al* 2001, Suh *et al* 2004, Sharrard *et al* 2008). However, even in hybrid LCAs there are several different options for the assessment, arising basically from the amount of process data used and the boundary established between process and IO data, both often subjective choices of the LCA practitioner. These choices may again lead to significant variations in the results.

3. Research design

3.1. Selection of the review materials

A literature search and review was conducted utilizing two different methods. First, a selection of applicable LCA studies was made based on the accumulated knowledge of the authors of the paper. This selection included mainly peer-reviewed academic studies but also included some professional reports. Then the selection was broadened following the snowball selection method, thus systematically going through the reference lists of the papers in the initial selection to find new papers and then repeating the same process with the applicable newly found studies. Altogether 76 cases from 31 studies were found with this method. This selection was then complemented by conducting a Google Scholar search with the following two key-word combinations, used individually: (1) ‘building life-cycle assessment’ and (2) ‘construction life-cycle assessment.’ This led to approximately 500 hits. The search was focused towards peer-reviewed academic journals and all other types of publications were rejected. After abstract screening, 35 papers were accepted for detailed reading, of which 16 included all the necessary information—in other words, GHG emissions or EE and the net or gross area of the building—for altogether 40 cases. Thus the overall number of cases is 116, representing 47 studies.

One problem detected in the screened LCA literature was that a significant share of the published studies did not report the research process in enough detail to enable an analysis of their scope and boundaries, which limited the number of studies that could be included in the review. Furthermore, in many studies the results were only given in figures (rather than written out numerically). These studies were included in the review if other selection criteria were fulfilled, but the presented numbers are only approximations (though precise enough for the purposes of this article).

The functional unit of the study, tons of GHG emissions per gross square meter (m^2), also restricted the case selections as building LCAs that did not report either the GHGs per gross or net m^2 or the needed information to calculate this could not be included. GHGs per gross m^2 was chosen as a unit as it was the preferred choice for the constructed area, rather than the GHGs per net m^2 unit in the reviewed studies. However, the studies that only reported EE were included by using an EE/GHG conversion factor presented later in this section. Additionally, with the studies that only reported the net areas of the construction projects, the net areas were converted to gross square meters using a net/gross area conversion factor, described in the next section. Roughly, *gross area* indicates the total constructed area while *net area* excludes the area covered by bearing partition walls and the outer walls of a building (Lylykangas *et al* 2013).

Finally, global warming potentials (GWPs) can be calculated over several specific time intervals, commonly 20, 100, or 500 years. In this review, GWP 100 was selected if several were presented in an article. Additionally, GWP 100 was also the assumed time interval if it was not defined otherwise in an article. Some uncertainty related to the comparability of the results of different studies over time relate to this issue since the GWP100 calculation guidelines of IPCC have evolved over time especially regarding gases other than CO_2. This is discussed further in section 4.3.

3.2. Functional unit conversions

As described above, certain conversions were necessary in order to enable comparisons between different studies. First, the net areas of the case buildings were converted into gross areas using a constant 0.7 m^2 of net area per m^2 of gross area when only the net area was known, based on Lylykangas *et al* (2013), which is in accordance with the respective factor taken from Passer *et al* (2012). However, these ratios are for residential buildings and thus the conversion might not be correct for office or public buildings. Additionally, the correct conversion factor might be different in a different location due to differences in architectural practices, traditions, or building codes. Although the conversion factor influences the absolute figures of the different cases, it has no significant influence on the conclusion of our study.

Second, a significant share of the reviewed studies only report EE (instead of GHG emissions) in the results. The EIO-LCA tool of Carnegie Mellon University (2008) was utilized as a reference in converting the EEs to GHGs. According to the EIO-LCA sector ‘Residential permanent site single- and multi-family structures,’ the EE–GHG conversion factor is 0.266 kg of GHG emissions per kWh. This is in line with other residential and commercial construction sectors—namely ‘Other residential structures,’ ‘Nonresidential commercial and health care structures,’ and ‘Other nonresidential structures’ (0.254–0.267 kg kWh^{-1})—in the EIO-LCA tool. This figure was also checked to be in accordance with, for example, the 0.235 kg kWh^{-1} figure of Junnila *et al* (2006) and the 0.252 kg kWh^{-1} figure of Fuller and Crawford (2011).

Finally, the results of the cases were converted into tons of GHGs per gross square meter (t CO_2e m^{-2}) according to the data reported in the studies.

3.3. Data description

Basic information about the 116 cases included in the review is presented in table 1. Eighty-six of the cases were assessed with process LCA, while in 19 cases hybrid LCAs were used and in 11 cases, IO LCA. The cases include various residential building types, commercial buildings, and communal buildings in different locations, although residential buildings are somewhat overrepresented. The cases were grouped into office buildings (*office* in table 1), apartment buildings (*apartment*), single-family homes (*detached*) and public buildings (*public*). The category *public* would include all public buildings but all the cases found are actually educational and research facilities. Table 1 also shows the case source, the year of the study, the gross area of the case building, the main material, the Köppen-Geiger climate classification (Peel *et al* 2007, Institute for Veterinary Public Health 2011) of the building location, and the scope of the assessment, presented as *only construction* or as the length of the reported use phase in the final column, meaning that the study included both the construction phase and the use phase.

3.4. Review process

To demonstrate the problems encountered in comparing the different building assessments, we analyzed the data from two different perspectives: the issues arising from the case (contextual issues) and the issues related to the actual LCA process (methodological issues). The analysis takes place on two levels: comparison of the numerical information from the reviewed literature and qualitative analysis of the underlying explanatory issues.

Of the two perspectives, the analysis of the contextual issues covers size, building type and design, the main material, and location. These should be the main factors causing differences in the assessment results, assuming that the LCA approaches are comparable to each other. For *building type* we use a four-category division of *detached, apartment, office* and *public building*. The main materials include concrete, steel, wood, and brick. For location, we employ the widely-used Köppen-Geiger climate classification scale (Peel *et al* 2007, Institute for Veterinary Public Health 2011). The case examples are located in ten different zones:

- Aw: equatorial, dry winters—for example, the outer margins of the tropical zones, occasionally an inner-tropical zone
- BSk: arid, steppes, hot summers—for example, some parts of Eurasia and Western Asia
- Cfb: warm, fully humid, warm summers—for example, central Europe and some parts of Australia
- Csa: warm, steppes, hot summers—for example, the Mediterranean area and some parts of Australia
- Csb: warm, steppes, warm summers—for example, north-western Italy
- Cwa: warm, desert, warm summers—for example, East Asia, the eastern coasts and eastern sides of continents
- Dfa: snow, fully humid, hot summers—for example, some parts of Canada and northern central Asia
- Dfb: snow, fully humid, warm summers—for example, the Midwest of the United States and some eastern parts of Europe
- Dfc: snow, fully humid, cool summers—for example, Scandinavia and other northern parts of Europe
- Dwa: snow, dry winters, hot summers—for example, some parts of China

The second perspective, methodological issues, refers to the case-by-case differences in conducting an LCA. To analyze these differences systematically through the assessment process, as a framework we adopted the commonly-used four-step LCA process of the ISO 14040 standard (International Standard Organization 1997): (1) goal and scope definition, (2) life-cycle inventory (LCI), (3) life-cycle impact assessment (LCIA), (4) interpretation (and reporting) of the results.

Although not all the LCAs in the review materials have followed the ISO standard, similar steps or equivalent decisions could be distinguished for each case, and thus these four steps provide a suitable framework for a comprehensive analysis. Different interpretations exist as well with regard to which step a certain problem belongs to. In this analysis, we handled each problem at the stage where the problem may actually materialize according to the following list:

1. Goal and scope definition
    a. method choice
    b. boundary definition
3. LCI
    a. variations in the comprehensiveness of LCI
    b. truncation error
3. LCIA
    a. homogeneity and proportionality problems
    b. IO sector selection
    c. sector-level aggregation

Table 1. The data for the literature review arranged according to the year of the study.

Year	Author	GHG (t gross m^{-2})	LCA method	Building type	Location	Köppen zone	Area (gross m^2)	Material	Assessment period (years)
1996	Cole and Kernan	0.32	Process	Office	CA	Dfc	4620	Wood	25/50/100
1996	Cole and Kernan	0.33	Process	Office	CA	Dfc	4620	Concrete	25/50/100
1996	Cole and Kernan	0.34	Process	Office	CA	Dfc	4620	Wood	25/50/100
1996	Cole and Kernan	0.35	Process	Office	CA	Dfc	4620	Concrete	25/50/100
1996	Cole and Kernan	0.36	Process	Office	CA	Dfc	4620	Steel	25/50/100
1996	Cole and Kernan	0.38	Process	Office	CA	Dfc	4620	Steel	25/50/100
1999	Winther and Hestnes	0.10	Process	Detached	NO	Dfc	157	Wood	50
1999	Winther and Hestnes	0.11	Process	Detached	NO	Dfc	157	Wood	50
1999	Winther and Hestnes	0.13	Process	Detached	NO	Dfc	157	Wood	50
1999	Winther and Hestnes	0.13	Process	Detached	NO	Dfc	157	Wood	50
1999	Winther and Hestnes	0.23	Process	Detached	NO	Dfc	157	Wood	50
1999	Trusty and Meil	0.28	Process	Detached	CA	Dfa	223	Wood	Only construction
1999	Trusty and Meil	0.34	Process	Detached	CA	Dfa	223	Steel	Only construction
1999	Trusty and Meil	0.42	Process	Detached	CA	Dfa	223	Concrete	Only construction
2000	Börjesson and Gustavsson	0.05	Process	Apartment	SE	Dfc	1679	Wood	50/100
2000	Börjesson and Gustavsson	0.08	Process	Apartment	SE	Dfc	1679	Concrete	50/100
2000	Thormark	0.33	Process	Detached	SE	Dfc	195	Concrete	Only construction
2000	Thormark	0.43	Process	Detached	SE	Dfc	195	Concrete	Only construction
2000	Fay *et al*	0.73	Hybrid	Detached	AU	Cfb	183	Wood	0/25/50/75/100
2000	Fay *et al*	0.79	Hybrid	Detached	AU	Cfb	183	Brick	0/25/50/75/100
2001	Saari	0.20	Process	Detached	FI	Dfc	135	Wood	50
2001	Saari	0.22	Process	Apartment	FI	Dfc	2447	Concrete	50
2001	Vares	0.20	Process	Apartment	FI	Dfc	1346	Concrete	100
2001	Treloar *et al*	0.50	Input–output	Detached	AU	Cfb	123	Concrete	Only construction
2001	Treloar *et al*	1.06	Hybrid	Detached	AU	Cfb	123	Concrete	Only construction
2002	Lenzen and Treloar	0.09	Hybrid	Apartment	SE	Dfc	1679	Wood	Only construction
2002	Lenzen and Treloar	0.11	Hybrid	Apartment	SE	Dfc	1679	Wood	Only construction
2002	Lenzen and Treloar	0.11	Hybrid	Apartment	SE	Dfc	1679	Concrete	Only construction
2002	Lenzen and Treloar	0.13	Hybrid	Apartment	SE	Dfc	1679	Concrete	Only construction
2002	Lenzen and Treloar	0.16	Hybrid	Apartment	SE	Dfc	1679	Wood	Only construction
2002	Lenzen and Treloar	0.17	Hybrid	Apartment	SE	Dfc	1679	Concrete	Only construction
2003	Junnila and Horvath	0.36	Process	Office	FI	Dfc	15600	Concrete	50
2004	Junnila	0.41	Process	Office	FI	Dfc	24000	Concrete	50
2005	Guggemos and Horvath.	0.55	Hybrid	Office	US	Dfb	4400	Concrete	50
2005	Guggemos and Horvath	0.62	Hybrid	Office	US	Dfb	4400	Steel	50
2006	Häkkinen and Wirtanen	0.04	Process	Public	FI	Dfc	7600	Wood	Only construction
2006	Häkkinen and Virtanen	0.12	Process	Public	FI	Dfc	7600	Concrete	Only construction
2006	Gustavsson *et al*	0.22	Process	Apartment	SE	Dfc	1700	Wood	100
2006	Gustavsson *et al*	0.26	Process	Apartment	FI	Dfc	1679	Concrete	100
2006	Gustavsson *et al*	0.26	Process	Apartment	FI	Dfc	1700	Concrete	100
2006	Gustavsson *et al*	0.30	Process	Apartment	SE	Dfc	1679	Wood	100
2006	Junnila *et al*	0.34	Hybrid	Office	US	Dfc	4400	Concrete	50
2006	Junnila *et al*	0.55	Hybrid	Office	FI	Dfb	4400	Concrete	50
2007	Häkkinen *et al*	0.38	Process	Office	FI	Dfc	9000	Concrete	100
2008	Haapio and Viitaniemi	0.10	Process	Detached	FI	Dfb	135	Wood	60/160
2008	Kofoworola and Gheewala	0.84	Hybrid	Office	TH	Aw	60000	Concrete	50
2009	Zabalza Bribián *et al*	0.26	Process	Detached	ES	Cfb	222	Brick	50
2010	Yan *et al*	0.38	Process	Office	HK	Cwa	43210	Concrete	Only construction
2010	Yan *et al*	0.53	Process	Office	HK	Cwa	43210	Concrete	Only construction
2010	Blengini and Di Carlo	0.63	Process	Detached	IT	Csb	367	Concrete	70
2010	Blengini and Di Carlo	0.77	Process	Detached	IT	Csb	367	Concrete	70
2011	Pasanen *et al*	0.19	Process	Apartment	FI	Dfc	2065	Wood	30/50/100

2011	Pasanen *et al*	0.27	Process	Apartment	FI	Dfc	2065	Concrete	30/50/100
2011	Fuller and Crawford	1.00	Input–output	Detached	AU	Cfb	84	Wood	100
2011	Fuller and Crawford	1.01	Input–output	Detached	AU	Cfb	101	Brick	100
2011	Fuller and Crawford	1.03	Input–output	Detached	AU	Cfb	130	Brick	100
2011	Fuller and Crawford	1.12	Input–output	Detached	AU	Cfb	149	Brick	100
2011	Fuller and Crawford	1.12	Input–output	Detached	AU	Cfb	170	Brick	100
2011	Fuller and Crawford	1.14	Input–output	Detached	AU	Cfb	195	Brick	100
2011	Fuller and Crawford	1.17	Input–output	Detached	AU	Cfb	214	Brick	100
2011	Säynäjoki *et al*	1.42	Input–output	Detached	FI	Dfc	35270	Wood	Only construction
2011	Säynäjoki *et al*	1.72	Hybrid	Detached	FI	Dfc	35270	Wood	Only construction
2011	Säynäjoki *et al*	2.01	Input–output	Detached	FI	Dfc	35270	Wood	Only construction
2012	Robertson *et al*	0.13	Process	Office	CA	Dfb	14233	Wood	50
2012	Gong *et al*	0.19	Process	Apartment	CH	Dwa	3913	Wood	50
2012	Gong *et al*	0.19	Process	Apartment	CH	Dwa	3913	Concrete	50
2012	Gong *et al*	0.55	Process	Apartment	CA	Dwa	3913	Concrete	50
2012	Kashkooli and Altan	0.22	Process	Office	UK	Cfb	87109	Concrete	50
2012	Kashkooli and Altan	0.22	Process	Office	UK	Cfb	87109	Concrete	50
2012	Kashkooli and Altan	0.22	Process	Office	UK	Cfb	87109	Concrete	50
2012	Robertson *et al*	0.42	Process	Office	CA	Dfb	14233	Concrete	50
2012	Passer *et al*	0.49	Process	Apartment	AT	Cfb	1609	Wood	50
2012	Passer *et al*	0.54	Process	Apartment	AT	Cfb	1980	Concrete	50
2012	Passer *et al*	0.66	Process	Apartment	AT	Cfb	1381	Wood	50
2012	Passer *et al*	0.67	Process	Apartment	AT	Cfb	970	Concrete	50
2012	Passer *et al*	0.77	Process	Apartment	AT	Cfb	1150	Concrete	50
2013	Thiel *et al*	0.39	Process	Public	US	Dfa	2262	Concrete	Only construction
2013	Asdrubali *et al*	0.36	Process LCA	Office	IT	Cfb	4790	Concrete	50
2013	Asdrubali *et al*	0.44	Process	Apartment	IT	Cfb	2610	Concrete	50
2013	Asdrubali *et al*	0.68	Process	Detached	IT	Csb	633	Concrete	50
2013	Thiel *et al*	0.49	Process	Public	US	Dfa	2262	Concrete	Only construction
2013	Thiel *et al*	0.39	Process	Public	US	Dfa	2262	Concrete	Only construction
2013	Ristimäki *et al*	1.10	Input–output	Apartment	FI	Dfc	21546	Concrete	25/50/100
2014	Azari	0.08	Process	Office	US	Csb	335	Brick	60
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2014	Azari	0.10	Process	Office	US	Csb	335	Brick	60
2014	Azari	0.10	Process	Office	US	Csb	335	Brick	60
2014	Azari	0.12	Process	Office	US	Csb	335	Brick	60
2014	Azari	0.12	Process	Office	US	Csb	335	Brick	60
2014	Takano *et al*	0.10	Process	Apartment	FI	Dfb	1243	Wood	Only construction
2014	Takano *et al*	0.13	Process	Apartment	FI	Dfb	1243	Steel	Only construction
2014	Takano *et al*	0.15	Process	Apartment	FI	Dfb	1243	Wood	Only construction
2014	Takano *et al*	0.18	Process	Apartment	FI	Dfb	1243	Concrete	Only construction
2014	Takano *et al*	0.20	Process	Apartment	FI	Dfb	1243	Concrete	Only construction
2014	Takano *et al*	0.21	Process	Apartment	FI	Dfb	1243	Brick	Only construction
2014	Biswas	0.52	Process	Public	AU	Csa	4020	Concrete	50
2014	Stephan and Stephan	1.39	Hybrid	Apartment	LE	Csa	1232	Concrete	50
2015	Takano *et al*	0.03	Process	Apartment	DE	Cfb	726	Wood	50
2015	Asadollahfardi *et al*	0.23	Process	Apartment	IR	BSk	1490000	Concrete	Only construction
2015	Asadollahfardi *et al*	0.23	Process	Apartment	IR	BSk	1490000	Concrete	Only construction
2015	Asadollahfardi *et al*	0.25	Process	Apartment	IR	BSk	1490000	Concrete	Only construction
2015	Lützkendorf *et al*	0.32	Process	Apartment	NO	Dfb	160	Wood	60
2015	Ajayi *et al*	0.12	Process	Public	CA	Dfb	2100	Wood	30
2015	Ajayi *et al*	0.35	Process	Public	CA	Dfb	2100	Steel	30
2015	Ajayi *et al*	0.38	Process	Public	CA	Dfb	2100	Brick	30
2015	Ajayi *et al*	0.39	Process	Public	CA	Dfb	2100	Brick	30
2015	Atmaca and Atmaca	0.42	Hybrid	Apartment	TU	Csa	471	Concrete	50
2015	Atmaca and Atmaca	0.74	Hybrid	Apartment	TU	Csa	4829	Concrete	50
2015	Ruuska and Häkkinen	0.43	Process	Apartment	FI	Dfc	3056	Concrete	Only construction
2015	Pöyry *et al*	0.47	Hybrid	Apartment	FI	Dfc	3056	Concrete	Only construction
2015	Zhao *et al*	0.47	Process	Office	CH	Dwa	133000	Concrete	Only construction
2015	Zhao *et al*	0.52	Process	Office	CH	Dwa	133000	Concrete	Only construction
2015	Zhao *et al*	0.54	Process	Office	CH	Dwa	133000	Concrete	Only construction
2015	Ajayi *et al*	0.58	Process	Public	CA	Dfb	2100	Concrete	30
2016	Sim and Sim	0.39	Process	Detached	KO	Dwa	110	Wood	30
2016	Roh and Tae	0.52	Process	Apartment	KO	Dwa	208392	Concrete	40
2016	Peng	0.64	Process	Public	CH	Cfa	16873	Concrete	50

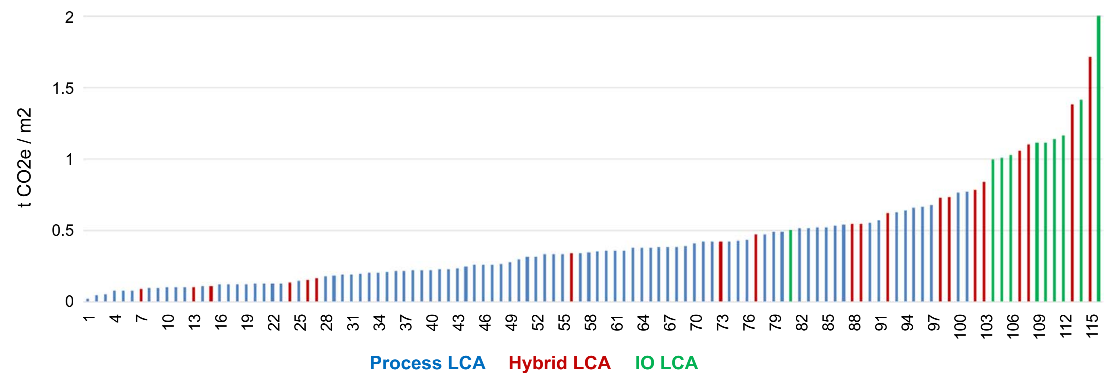

Figure 1. GHG emissions per gross m^2 of the reviewed case studies.

4. Interpretation of the results and reporting
    a. transparency
    b. replicability
    c. validity
    d. reliability

4. Analysis and discussion

4.1. General examination of the case results

Huge variation in the GHGs per square meter was found in the analyzed cases, but overall the results form a relatively steadily increasing series, except for a few upper-end cases, as figure 1 shows. Takano *et al* (2015) and Häkkinen and Wirtanen (2006) have reported the lowest emissions, 0.025 and 0.04 tons of $CO_2e\ m^{-2}$, and Säynäjoki *et al* (2011) the highest, 2.00 tons of $CO_2e\ m^{-2}$. Both Takano *et al* (2015) and Säynäjoki *et al* (2011) evaluate residential buildings located in the same Dfc climate zone. From the methodological perspective, Takano *et al* use process LCA whereas Säynäjoki *et al* use IO LCA. In addition, the scope of Säynäjoki *et al* is very wide, including the whole area with infrastructure construction, while in both Takano *et al* and Häkkinen and Wirtanen the scopes are significantly more limited, mainly including the structure and envelope of the building, due to the comparative LCA nature of their study. The lower-end estimate of Takano *et al* (2014a) of 0.2 tons of $CO_2e\ m^{-2}$ and the higher-end estimate of Ristimäki *et al* (2013) of 1.1 t $CO_2e\ m^{-2}$ provide another interesting example of the variation in the published results because both studies address concrete structure apartment buildings in a cold climate zone. The potential sources for these differences are discussed in the following sections.

The above examples included different LCA methods, but even within each method the scale of reported results is wide. In process LCAs the highest reported emissions are 0.77 t $CO_2e\ m^{-2}$ (Blengini and Di Carlo 2010), whereas the lowest with IO LCA are 0.50 tons of $CO_2e\ m^{-2}$ (Treloar 2001). In hybrid LCAs the scale runs from 0.09 tons of $CO_2e\ m^{-2}$ (Lenzen and Treloar 2002) to 1.72 tons of $CO_2e\ m^{-2}$ (Säynäjoki *et al* 2011).

Furthermore, while the largest emissions exceed the lowest by a factor of 50 and within the same method the scales are wide as well, in single studies with multiple cases the variation is substantially lower. Among these, Ajayi *et al* (2015), Winther and Hestnes (1999), and Asdrubali *et al* (2013) have reported the largest variation but only in Ajayi *et al* (2015) do the emissions more than double from the lowest case to the highest case. It thus seems that within a study the assessment choices and assumptions are similar for each case and the results are also consistent but the consistency is lost when the sample includes different studies.

Overall it is very unlikely that the main explanation for the differences would be just the building characteristics—rather they could be explained to a significant extent by the scope and methodological choices. In the next two sections we first examine the contextual and then the methodological issues potentially causing the huge differences observed.

4.2. Contextual issues: the properties of the cases

The reviewed cases are different in numerous aspects, and were the LCAs all comparable with each other, these differences would explain the variation in the reported results. We selected four key characteristics that are likely to cause the majority of the variation in case properties for a more detailed analysis: building type, main material, size, and climate zone. Were these qualities to explain the variation in the results of different cases, the results within each category should have low variation, whereas in the opposite case, no clear patterns should be found.

The results are visualized in figures 2(*a*)–(*d*). It seems obvious that none of the presented four characteristics explains much of the variation in the results of different studies. Within each group in figures 2(*a*)–(*b*) and 2(*d*) the variation is significant whenever there are multiple studies in a certain

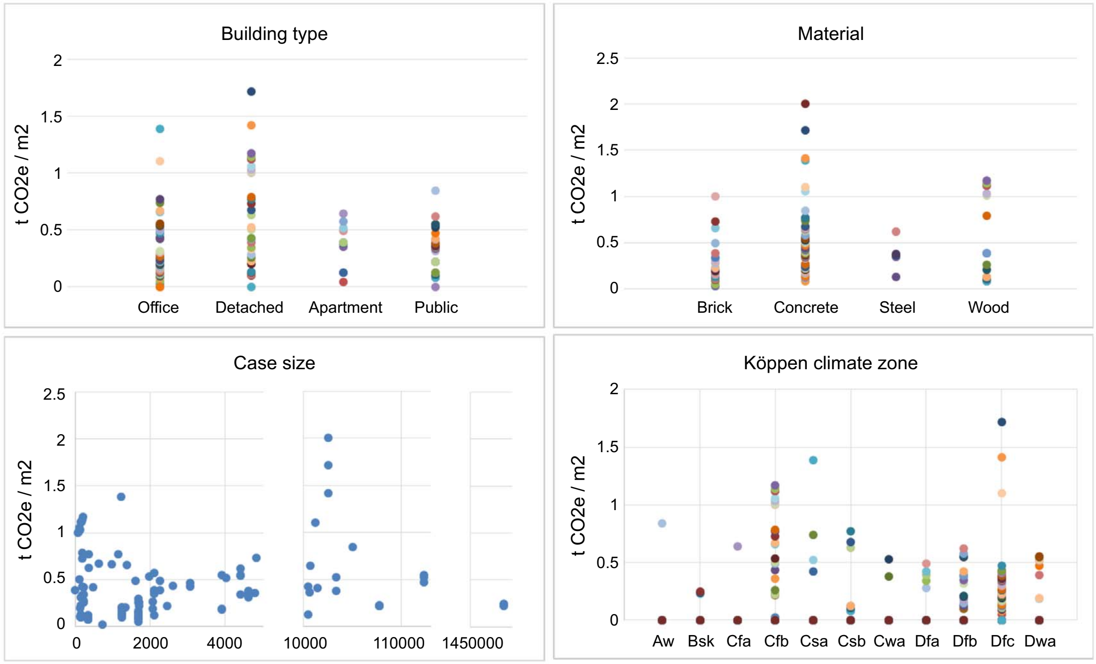

Figure 2. The results of the 116 case studies according to the building types, materials, sizes, and climate zones showing the wide variation even within similar classes of buildings.

category. In figure 2(*c*) there is no correlation between the case size and the reported GHGs.

When looking at the data in more detail, regarding the building type the detached buildings have higher average emissions (0.64 t CO_2e m^{-2}) than the other building types (0.3–0.4 t CO_2e m^{-2}), but the scale is wide, as figure 2 shows. A potential explanation for the differences could be the unique building designs, which could explain significant differences in the emissions even from buildings having the same classification. This kind of variation is especially evident in the residential sector, where the scale in the reported results is the widest. For example, Atmaca and Atmaca (2015) explain that a multi-story building has higher emissions per m^2 than their other, smaller residential case building due to the higher quality, more cement-intensive, concrete. Offices, on the other hand, might be more uniform globally, but the sample is also very small and the random factor could be significant. Unfortunately, these kinds of differences could not be systematically captured in this analysis, and in any case they form an important challenge for using LCA to inform policy-making.

The variation of the building sizes is significant, ranging from an 80 m^2 single detached house to a 1 490 000 m^2 residential area, but no clear pattern can be recognized related to the size. One important deficiency in this analysis is that the above-mentioned differences in scope may hinder the size-related patterns from showing. Furthermore, groundworks and substructures are highly dependent on the site qualities, particularly soil stabilization needs, and can have a significant impact on the results (Ruuska and Häkkinen 2015), but it is often not at all clear how these potentially affect the results of a certain study.

The cases are located in Scandinavia, Southern Europe, the United States, the Middle East, Asia, and Australia. Climates thus differ between the case locations but do not explain the difference in the LCA results, as seen from figure 2(*d*); in most of the climate zones the within-zone variation is significant and do not show any pattern across the zones e.g. from colder to warmer zones. Furthermore, even for similar buildings the within-zone variation remains high. For example, Börjesson and Gustavsson (2000) report 0.08 t CO_2e m^{-2} emissions for a concrete-frame apartment building in Dfc zone, whereas Ristimäki *et al* (2013) report 1.1 tons m^{-2} for a residential area consisting of similar concrete-frame building. Similarly, Zabalza Bribián *et al* (2009) assessed a brick-covered detached house in Cfb zone at 0.26 t CO_2e m^{-2} whereas in Fuller and Crawford (2011) similar detached houses run from 1.01 to 1.17 tons m^{-2}. In Csa Atmaca & Atmaca's two concrete-frame apartment buildings of 471 m^2 and 4829 m^2 are estimated at 0.42 and 0.74 t CO_2e m^{-2}, whereas Stephan and Stephan (2014) give an estimate of 1.39 t CO_2e m^{-2} for a concrete-frame apartment building of 1232 m^2.

The contextual issues related to the LCAs certainly have an influence on the results of the assessments. However, according to the above analyses, they hardly explain the huge variation reported in the review literature. Thus, methodological issues inevitably have an important role. They are examined next, according to the process described in section 3.4.

4.3. Methodological issues: the characteristics of the LCA process

The four steps of the ISO 14040 framework for LCA are used to structure the analysis of the methodological differences, as explained earlier. It is shown that each step includes decisions that profoundly affect the assessment outcome but are not sufficiently guided by the standard and thus lead to high variation in assessment results, even when different assessments follow the standard.

1. **Goal and scope definition**

   In the first step the scope of the assessment is decided both horizontally and vertically: the building components and functions are included and the length of the included production and delivery chain in the LCI phase is determined. These decisions affect the assessment outcome profoundly, but can vary substantially between different studies, even when the ISO guidelines are followed.

   The assessment scope is the first factor that can cause significant differences in the results. In the reviewed literature some studies only include the main materials. The claim is that the main materials give a good enough approximation of the emissions. Alternatively, the aim of the study might concentrate on comparing certain aspects of the building design and thus excluding some details of building construction from the LCA might be well reasoned. However, the results of the studies with narrow scopes tend to be placed in the lowest end within the reviewed literature, and thus anyone who utilizes the results for decision-making should be well aware of the selected scope. For example, Häkkinen and Wirtanen (2006) have only included the structure and envelope of the case buildings and report very low emissions in comparison to the average of the reviewed literature. Rather low emissions are also reported by Takano *et al* (2014a) who also concentrate on comparing structure materials and operate with a relatively narrow scope. Börjesson and Gustavsson (2000), and Gustavsson *et al* (2006), who have also reported emissions well below the average, exclude the construction site. The construction site is included in, for example, Saari (2001), Junnila and Horvath (2003), and Blengini and Di Carlo (2010) and has been reported to increase the emissions by 3%–15% in them. Furthermore, the technical building equipment is often left out of the assessments (e.g. Börjesson and Gustavsson 2000, Zabalza Bribián *et al* 2009, Pasanen *et al* 2011) but is reported to cause 7% of the emissions in Junnila *et al* (2006). Thiel *et al* (2013) report photovoltaic system and geothermal wells to contribute 0.1 t CO_2e m^{-2}, 20% of their overall estimation. At the highest end of the reported emissions, Stephan and Stephan (2014), and Säynäjoki *et al* (2011, 2012) include the technical equipment and the construction site but also the infrastructure of the assessed case area. Of them, Säynäjoki *et al* (2012) report this to increase the emissions estimate by approximately 10%. Heinonen *et al* (2016) particularly studied the cutoff impact of the horizontal scope decision and depict how common cutoffs can affect the result by tens of percentage.

   The goal and scope definition of an assessment also sets the conditions for choosing the appropriate LCA application, which seems to be one of the most important decisions with regard to the results due to the inherent differences of the different LCA methods with regard to the boundary definition of a study. Even in the most comprehensive process LCA the number of included upstream and downstream processes needs to be decided, and certain processes are always left outside the boundary. Even though this is actually a bias that leads to lower-than-actual results, the problem is called *truncation error.*

   On the other hand, in IO LCAs the boundary is infinite with regard to the included processes. Thus the results of IO LCAs should inherently be higher than those of process LCAs (as brought up in previous studies by, e.g. Hendrickson *et al* (1998) and Junnila (2006), and demonstrated by Lenzen (2000)). However, IO and hybrid LCAs suffer from *aggregation error,* arising from the aggregation of several potentially different industry sectors into each IO table sector, which can lead to the assessment either underestimating or overestimating the actual emissions. Still, IO LCAs and IO-based hybrid LCAs are often considered to lead to increased emissions in comparison to process assessments. IO and hybrid LCAs are also likely to reach wider scopes than process assessments. There can be thousands of articles in one modern building, and even the most comprehensive process assessment is likely to exclude some share of them, whereas in monetary unit–based IO models all the costs can easily be included.

   In the reviewed literature the boundary definition related differences in the LCA methods can be at least partially captured by looking at the average emissions reported with different methods. According to these, the difference between the methods is clear: in the 86 process-LCA cases the average emissions are 0.31 t CO_2e m^{-2}, whereas in the 19 hybrid LCAs the average is 0.58 t CO_2e m^{-2}, and in the 11 IO LCAs 1.15 t CO_2e m^{-2}. In addition, Lenzen and Treloar (2002), employing hybrid LCA but keeping the same scope, reported two times higher emissions from the case studied earlier with process LCA, by Börjesson and Gustavsson (2000). In the hybrid assessments of Pöyry *et al* (2015) the share of IO analysis is low and placed well below the average of hybrid assessments (0.47 t CO_2e m^{-2}), whereas in Säynäjoki *et al* (2012), the highest end reported is very high (1.7 t CO_2e m^{-2}). These examples and the whole analysis only give an indication of what might be the contribution of method selection. The highest reported process results are clearly higher than the lowest end of IO results, as depicted by figure 1, but process analyses dominate the lower end overall.

One important issue is if the potential positive GHG effects are taken into account. Wooden materials are a well-known carbon sink and, for example, in Robertson *et al* (2012) and Takano *et al* (2015) the inclusion of this quality of wood largely explains the very low GHGs. However, it is not straightforward to account for the GHGs from wood usage and actually several very important choices and assumptions need to be made in order to assess the full life-cycle GHG impact of wood as a construction material (Häkkinen and Haapio 2013). For example, Häkkinen and Haapio (2013) point out that the sink feature of wood should only be given credit in circumstances where the utilized forests are actually grown back. On the other hand, in the long run, concrete acts as a sink as well. According to Kjellsen *et al* (2005) the carbonization process of concrete can absorb 20%–40% of the emissions embodied in concrete product manufacturing during the building's life cycle. Thus including or excluding the sink perspective can significantly affect the results. In addition, concrete types are in development that absorb more CO_2 than was emitted during their production (Imbabi *et al* 2012).

Finally, the boundary can be extended to include other-than-construction end uses of the materials after demolition of a building. Börjesson and Gustavsson (2000) assume the wooden materials to replace fossil fuels when used for energy production at the end of their life cycle and calculate this as a net positive effect for the building. Gustavsson *et al* (2006) included energy use of the forest residues from logging and wood processing in their assessment. Their analysis actually represents the widest effects of fossil fuel substitutions across the whole literature reviewed, although they partly allocate the positive impacts to the later life-cycle phases of the case building.

2. LCI

According to ISO 14040, the LCI phase consists of data collection and calculation processes in order to quantify the inputs and outputs of a production system. Although LCI follows the decisions in the goal and scope definition step, several important choices relate to LCI as well.

Firstly, even if the boundary definitions of different studies were similar, the extensiveness of an LCI can differ significantly. As mentioned, there can be thousands of different items in a modern building. Construction processes are often fragmented, with several sub-contractors taking care of their shares. Thus conducting a comprehensive LCI is difficult and may require a lot of resources, and it is not surprising that all the actually used items are rarely included in an LCI. Within the cases assessed with process LCA in the reviewed literature, Passer *et al* (2012) rank as having the most GHG intensive case, and it also has some of the widest LCIs in the sense of the included items. Their LCI is based on the Austrian Standard ÖNORM B-1801-1 and includes 1700 items. While the wide LCI partially explains the results reported by Passer *et al* (2012), one general problem in evaluating the literature is that the LCIs are often only described very briefly and drawing precise conclusions is difficult. We analyze this issue further below with other reporting-related problems.

Despite the extensiveness of LCI, a process LCA is never capable of including all of the almost indefinite number of higher-order upstream tiers of the product manufacturing processes related to all the thousands of construction products used in a single building. The truncation error is always present. Furthermore, it is not known how many upstream and downstream tiers the LCA practitioner should include to reach the comprehensiveness target set in the definition of the goal and scope. The impacts of the excluded tiers vary by product and can be high (e.g. Lenzen 2000, Hendrickson *et al* 1998). According to Lenzen (2000) even the relatively extensive process LCAs do not reach reasonable system completeness and thus lead to unreliable or incorrect conclusions. This is the main reason for Lenzen and Treloar (2002) coming to the conclusion that EE in the building materials was underestimated by a factor of two in the process LCA study of Börjesson and Gustavsson (2000). In addition, Lenzen (2000) compared the truncation errors of Australian industry sectors using a simplified process LCA with various numbers of upstream processes included in the assessment. Only including the direct energy consumption of an industry usually leads to a truncation error of over 50%, and even including the all second-order input paths usually results in a truncation error of more than 30%. The finding that an increasing share of IO data in hybrid LCAs seems to lead to elevated emissions also supports this claim.

Another type of source for inaccurateness in LCA results arises from input data quality. The material quantities are seldom actually utilized quantities but are rather up front estimates, and the same applies for cost data in IO assessments. At the beginning of the design process the estimates tend to be inaccurate and improve towards the end. Therefore, depending on the utilized data source, the input data quality can be an important source of inaccuracy.

3. LCIA

The association of LCI data with specific environmental impacts and understanding the impacts are the tasks of this phase. The uncertainty of the sources in the different LCA methods is slightly different in nature but for each method several problems exist.

IO LCAs and hybrid LCAs suffer especially from three important limitations in the LCIA phase: homogeneity problems, proportionality problems, and sector-level aggregation. The homogeneity problem means that all the products of one IO sector are assumed to have the same environmental burdens per a certain monetary transaction in the sector. The proportionality problem means the inherent, but not very realistic, assumption that the relationship between the price and the environmental burdens of one sector are linear. Thirdly, the aggregation problem arises from the condition of all currently existing IO models, which potentially significantly different industry sectors, are aggregated into one IO sector. The sectoral environmental data is thus highly aggregated as well and only describes the averages of several industries, and can either overestimate or underestimate the actual emissions. More profound presentations of these problems can be found from, for example, Crawford (2011), Hendrickson *et al* (2006), and Suh *et al* (2004), but it is evident that these may significantly affect the assessment results. It is also very problematic, that these weaknesses of IO LCAs are errors in nature, and one cannot even evaluate in which direction the problems push the results without an extensive analysis of the utilized IO tables. Thus, it cannot be analyzed from the review data how significantly these problems affect the IO and hybrid LCA results included in the review. Although the review only concentrated on GHG emissions it is worth mentioning that IO tables only include a limited amount of impact categories compared to most process LCA databases, which limits the general usability of IO LCAs.

The three errors inherent in the LCIA of IO LCAs are still claimed to be significantly smaller than the truncation error of a typical process LCA (Lenzen 2000). Su *et al* (2010) also suggest that when the number of sectors in an IO model increases to above 40, the aggregation error is no longer a very significant factor. Furthermore, Wiedmann (2010) has presented that the different nature of the LCIA problems of IO LCAs leads them to cancel out each other and significantly reduce the impact. The above-presented figures, showing that the assessment results tend to decrease as the share of process data increases, support this claim, but with the utilized data the issue cannot be investigated further.

Even though process LCAs do not suffer from the above-described problems, there are sources of similar types of uncertainty associated with them as well. Firstly, despite being considered accurate in a data sense, the impact data is actually often average data that may often concern some foreign country. For example, according to Crawford (2011), since product-specific data might be unavailable or difficult to obtain, LCAs often utilize pre-compiled LCIA databases that only provide an aggregation of numerous products of a similar kind within one country or region. Further, as products or processes become more detailed, the aggregated product or process in a database might be significantly different from the actual object of the study. This problem is also an error in its nature, and thus the direction of how it affects the LCA results cannot be easily analyzed.

The majority of the process LCA studies included in this review have utilized life-cycle calculation programs—for example SimaPro, GaBi or KCL-ECO—that use environmental effect databases and method compilations, such as Ecoinvent. While these are claimed to enable transparent and comparable analyses (Asdrubali *et al* 2013), they might actually not be very accurate as not all materials are available, nor are data for different production conditions. Furthermore, even between the programs there can be important differences in the sectoral emissions intensities (Herrmann and Moltesen 2015), and, as demonstrated by Takano *et al* (2014b), on a building level the results of an assessment can vary quite a lot depending on the utilized database. Furthermore, some studies report having utilized intensity values from elsewhere, which further compromises the comparability between studies. For example, Yan *et al* 2010 took the GHG intensities for the different construction materials from previous literature and, for a major part, they are not even of the same magnitude as those from the databases of the most widely utilized programs: SimaPro and GaBi. Still, of course it is possible that they describe the local production conditions well. Yan *et al* (2010) also compare the impact of utilizing virgin or recycled materials and find the GHG emission reduction potential of recycled materials to be as high as one third. Thus the recycling rate, or the assumed recycling rate, can also play a major role. An important issue when calculating the credit from end-of-life recycling for the building under assessment is that the LCA practitioner should use the intensities of virgin materials to begin with in order to avoid double counting. A common practice is to estimate the recycling rate of the actual construction materials and then of course no additional credit from the end-of-life recycling should be given for the same building.

One common problem related to both approaches is that the environmental data is rarely up to date. Due to, for example, technological development and temporal changes in production fuels, the databases predominantly utilized in building LCAs are inevitably quickly become out of date. In many cases the problem is probably minor, but especially in IO LCAs, the IO tables are seldom updated continuously. Another time-related issue is that the calculation methods evolve over time, and the outcome can be different depending on which IPCC guidelines are utilized. This should not pose a major problem with regard to climate change, especially in the building sector assessments, due to the dominant role of CO_2, but changes occur and, especially with other impact categories, the calculation methods can change rapidly.

Hybrid LCAs, which fall in between the process methods and the IO methods, are supposed to combine the strengths and reduce the weaknesses of the two basic approaches (Suh *et al* 2004). However, since both carry associated uncertainties regarding the same issues, hybrid models do not actually inherently reduce the uncertainties as much as they change the profile of the problems. Of course, if the employed process data in hybrid LCAs is actually process or product specific, they can truly reduce the uncertainties.

We showed earlier how in our data that hybrid assessments provide estimates from somewhere between process and IO assessments, which also complies with the hypothesis. However, due to the nature of the errors causing the problems associated with each LCA method, in any particular case the hybrid data may push the outcome of the initial assessment in any direction. For example, Rowley *et al* (2009) reported a hybrid analysis to increase the emissions by 20% in comparison to both IO LCA and process LCA. An additional issue with hybrid LCAs is that the structures and characteristics of the hybrid models differ significantly between studies and the shares of process and IO analyses within models are incomparable between studies.

Finally, IO sector selection is a step in the LCIA of IO LCAs and hybrid LCAs that may significantly affect the results. For example, most IO LCA models incorporate a general residential construction sector that features not only the national average of residential construction but certain construction material sectors as well. A common first step of IO LCAs is to allocate all costs to the average single sector and then using the detailed categories allocate costs more precisely into various material and construction work sectors. Comparing the results of these two stages gives a good example of how strongly the sector selections affect the results. The reviewed hybrid LCA literature includes two such cases. Treloar *et al* (2001), in Australia, reported the single-sector IO LCA analysis to result in 0.44 t $CO_2e\ m^{-2}$ (6,8 GJ) whereas their final detailed analysis of the same building resulted in 0.94 t $CO_2e\ m^{-2}$ (14,3 GJ). In Säynäjoki *et al* (2011) a similar single-sector screening IO was carried out, resulting in 67% of the later multi-sector IO LCA.

4. Interpretation of the results and the standards of reporting

The interpretation phase combines and analyzes the findings from the inventory analysis and impact assessment. The ISO 14040 standard states, the 'results of the LCA shall be fairly, completely and accurately reported to the intended audience.' The level of detail in reporting enables or hinders the reader's potential to evaluate the LCA process, and the validity and reliability of the results. Without transparent reporting, the comparability and replicability of LCA studies are lost as the reasons for result variations appear to arise from assumptions, and methodological and data choices rather than from case properties. Decision-making based on the comparison of separate LCAs without proper knowledge of the underlying assumptions and choices made during the studies could lead to unwarranted or wrong decisions.

The outcome of our literature synthesis reveals a poor comparability between the results of the various studies, even when the same LCA method was reported to have been used. For a large share of the reviewed literature, the exact scope of the study could not be defined, thus rendering comparisons impossible. The critical implication is that separate studies for the same case building with the same initial data may lead to opposite conclusions when the practitioners use different LCA approaches and assumptions.

5. Conclusions

The study was set to evaluate how coherent an understanding the scientific community has of the lifecycle GHG impacts of building construction and if

LCA seems to be able to provide reliable results to supporting policy-making in the building sector. Due to the significant contribution of the sector to global environmental burdens, buildings pose a great example of a sector where the need for reliable data is great. According to our analysis, however, currently it seems that LCA is inconsistent and cannot provide reliable data for decision-making in the building sector without further development. The majority of the studies suggest that the embodied emissions are minor compared to the use phase emissions, but if the presented higher end estimates are considered, the embodied emissions should be given significant weight. Part of the problem lies in the overly loose guidelines on conducting an LCA, but partially it also lies in the practitioners' ways of implementing LCA without strictly following the guidelines.

Through an analysis of the contextual and methodological issues related to the LCAs, we depicted how the variation in the reported building pre-use phase GHGs arising particularly from the methodological choices is dominant. In 1993 an early version of Guidelines for Life-Cycle Assessment, 'A Code of Practice' stated, 'it is not possible to define rigid methodological rules for all aspects of LCA because the technique is still in development' (SETAC 1993). In 2007 Nässen *et al* suggested that IO assessment led to twice the magnitude of the estimates obtained with process assessments. Now it seems that even today, LCA practices are still not established enough in the sense of there being consistent methodologies across different assessments, which leads to incomparable LCA results. As expressed by Lasvaux *et al* (2014), concerning their work on LCA standardization in the European building sector, 'the lack of consistent, practically applicable metrics and guidance for practitioners on how to conduct consistent LCA studies [. . .] and different levels of experience of LCA practitioners presents a considerable barrier to the widespread use of LCA in Europe's construction sector.'

We depict how the reported GHG emissions and EE vary by a factor of 20 from the lowest decile to the highest decile and how the vast majority of this variation is by no means explained by the characteristics of the different buildings, but rather it is explained to a large extent by the differences in the LCA methods and the subjective choices made by the LCA practitioner. These method-related variations could easily be significant enough to completely change the policy implications were the information provided with a different method. Furthermore, while the most important advantages and disadvantages of the different LCA methods are common knowledge and discussed extensively in the literature (e.g., Crawford 2011, Hendrickson *et al* 2006, Suh *et al* 2004), the bias/error analyses rarely consider the method choice itself when compared to other LCA approaches, or at least go as far as to quantify the impact.

One of the most obvious examples of why the current situation is unsatisfactory is the policy recommendation arising from building LCAs for building life-cycle GHG mitigation. If the lower-end of the reported results holds true, the construction phase has little significance in the life-cycle emissions of a building and mitigation efforts should be targeted to the use phase (as suggested by, e.g., Börjesson and Gustavsson (2000) and Winther and Hestnes (1999)), which is the prevailing orientation. However, if the higher end is looked at, the policy implication is very different and the construction-phase emissions of new buildings seem high enough to dominate all emissions for decades (Fuller and Crawford 2011, Säynäjoki *et al* 2012). Generally, pre-use phase emissions are tied to the use phase, so making the decision on an individual life cycle stage without considering the others leads mainly to incorrect decisions.

Finally, in this analysis we concentrated solely on the construction phase, including the materials. However, building LCAs are often utilized to find the most relevant mitigation possibilities over the building life cycle. This gives rise to another problem in building LCAs, namely that of the assumed building life cycles. If the assumed life cycles were uniform or were based on strong knowledge, the issue would be of less significance. However, the life-cycle assumptions usually follow very generic 25/50/100 year options with one or all of them being presented. From the decision-making perspective it is evident that this kind of variation in the assumed life cycles affects the policy implications significantly.

When the complexity of buildings as an object of LCA is taken into account, it is debatable whether the practices and guidelines for uniform LCA are even possible. Furthermore, setting the guidelines for uniform LCA would at worst stop the development of the methodology and decrease the representativeness to the various dimensions of actual modeling objects (e.g., recycling and carbon sink perspectives). Despite causing variation between the studies, new viewpoints would very likely increase the scientific potential of the LCA methods. By setting one model for 'official LCA,' all such development could be less attractive for LCA practitioners. Currently, building certifications, e.g., LEED v4, are considering the inclusion of LCAs into their rating tools (Owens *et al* 2016). The determination of LCA method and the requirements for the modeling process should unify the field to some extent. On the other hand, it could decrease the relevenace of the components excluded from the requirements even further. However, certification guidelines for LCAs are definitely an important space to watch.

The 'complete LCA' that delivers all and exact information of the real-life building would include indefinite amounts of data and viewpoints: construction components, upstream processes, and recycling scenarios, to name just a few. Additionally, these are just themes related to climate change. The 'complete LCA' should take all the other environmental effects into account as well and all of those have numerous viewpoints similar to those in GHG analysis. Thus, conducting such an LCA would be practically impossible and definitely not plausible for the environmental reporting of companies. On the other hand, leaving some viewpoints out of LCA would favor some construction materials or life-cycle phases over others.

In academia, striving towards as complete an LCA as possible should be encouraged. Adding increased knowledge to LCA is essential for developing LCA methods to provide a better reflection of reality. One step towards more comprehensive and more accurate assessments would be an open global database collecting and comprising all building sector LCAs, managed and updated by the LCA practitioners themselves. The database could also include the cost and quantity data of individual studies whenever publicly shareable. However, the most important suggestion for LCA practitioners is that the qualities of LCAs should be reported extensively and visibly enough so that decision-makers with decent knowledge of LCA methodology can make well-informed decisions. Currently the variation due to subjective choices in all the major LCA process phases is so great that the published building LCAs do not offer a solid enough so background information for policy-making without a deep understanding of the premises of a certain study and good methodological knowledge. Additionally, incomplete reporting of methodological detail and parameters of LCAs make it challenging for experts in the field as well. Given the high and poorly explained variance in LCA studies reviewed, we call on the field to do a better job of being transparent.

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