THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Simplifying LCA use in the life cycle of residential buildings in Sweden

SJOUKE BEEMSTERBOER

Department of Architecture and Civil Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2019

Simplifying LCA use in the life cycle of residential buildings in Sweden

SJOUKE BEEMSTERBOER

Department of Architecture and Civil Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Chalmers Reproservice
Gothenburg, Sweden 2019

Simplifying LCA use in the life cycle of residential buildings in Sweden

SJOUKE BEEMSTERBOER
Department of Architecture and Civil Engineering
Division of Building Technology, Sustainable Building
Chalmers University of Technology

Abstract

This thesis discusses the use of environmental life cycle assessment (LCA) in the building life cycle. While the life cycle of a residential building is an important source of environmental concern, knowledge about LCA remains scarce and sporadic in most construction companies. In anticipation of a regulatory requirement for LCA-based climate declarations, construction companies in Sweden are expressing increasing interest in applying LCA to residential buildings. However, despite this interest, many companies experience difficulties making effective use of the potential that LCA may have to shape environmental action in the building process.

The aim of this licentiate is to clarify the conditions that hinder a more effective use of LCA. It addresses whether LCA is too complex to be used effectively, and whether there are other conditions that may require attention. In addition, it examines whether simplification of LCA may be a meaningful way to stimulate LCA use in the building life cycle.

A literature-based exploration of LCA use in the building context was conducted. The results of this exploration identify central problems with LCA use for residential buildings and focus specifically on the complexity of building LCA. In addition, this licentiate provides an empirically informed account of the experiences and perceived problems with residential building LCA in Swedish construction companies. Perceptions of LCA analysts and environmental managers were explored in an interview-based study. In addition, nine LCA studies were conducted on multifamily residential buildings using data from these construction companies.

The findings in this licentiate indicate that while complexity should not be discounted, it cannot explain the ineffective use of LCA in the building life cycle. Even if LCA may be difficult to understand, the types of complexity involved are not essentially different from those tackled successfully elsewhere in the building process. In addition, there are several other reasons that explain why LCA is considered difficult to use. Problems with demand, resources, data availability, and competence all contribute to an environment in which performing LCA is more difficult than necessary.

A review of available LCA simplification strategies is presented to tackle complexity in building LCA. A systematic search and review was conducted using the simplification literature. The results suggest a wide variety of established simplification techniques, following five central simplifying logics: exclusion, data-substitution, expert judgement, standardisation, and automation. These simplification strategies can be used to more easily apply LCA in a building context.

In 2022, the use of LCA-based climate declarations will become a state requirement in the Swedish building sector. In order to make more effective use of LCA in the building life cycle, it is not enough to merely apply LCA to calculate the greenhouse gas emission of a finished building design. If the ambition is to make use of the full potential of LCA for industry and ecology, it is necessary to more actively integrate LCA in the planning, design, and construction of residential buildings.

Key words: Life cycle assessment (LCA), Simplified LCA, Life Cycle Management (LCM), building construction, multifamily residential building

Simplifying LCA use in the life cycle of residential buildings in Sweden

SJOUKE BEEMSTERBOER
Institutionen för Arkitektur och samhällsbyggnadsteknik
Avdelningen för Byggnadsteknologi, Hållbart byggande
Chalmers tekniska högskola

Sammanfattning

Denna licentiatuppsats diskuterar användningen av livscykelanalys (LCA) i byggnader. Medan livscykeln av en byggnad har en stor miljöpåverkan är kunskapen om LCA fortfarande begränsad och sporadisk i de flesta byggföretag. I väntan på ett lagkrav för LCA-baserade klimatdeklarationer visar byggföretag i Sverige ett ökande intresse för att tillämpa LCA på bostäder. Trots intresse upplever dock många företag svårigheter att effektivt utnyttja den potential som LCA kan ha för att påverka miljöåtgärder i byggprocessen.

Syftet med denna licentiatuppsats är att få en bättre förståelse om de villkor som hindrar en effektivare användning av LCA. Uppsatsen behandlar frågan huruvida LCA är för komplext för att användas effektivt eller om det finns andra aspekter som kan behöva uppmärksamhet. Dessutom undersöker studien om förenkling av LCA kan vara ett meningsfullt sätt att stimulera användning av LCA i byggnader.

En litteraturstudie av LCA-användning i byggnadssammanhang har genomförts. Resultaten från denna studie identifierar centrala problem med LCA-användning och fokuserar specifikt på komplexiteten av livscykelanalyser för flerbostadshus. Dessutom har en empiriskt informerad redogörelse om erfarenheter och upplevda problem med LCA av bostadsbyggnader i fem svenska byggföretag genomförts. Uppfattningar från LCA-analytiker och miljöchefer har undersökts i en intervjubaserad studie. Därutöver har nio LCA-studier på flerbostadshus genomförts med uppgifter från dessa byggföretag.

Resultaten i denna licentiatuppsats visar att även om komplexiteten av LCA inte bör bortses ifrån, kan den inte förklara den ineffektiva användningen av LCA i byggnader. Även om LCA kan vara svårt att förstå, skiljer sig de olika typerna av LCA-komplexitet inte väsentligt från de som framgångsrikt har hanterats på andra håll i byggprocessen. Dessutom finns det flera andra skäl som kan förklara varför LCA anses vara svårt att använda. Problem med efterfrågan, resurser, datatillgänglighet och kompetens bidrar till att göra LCA svårare än nödvändigt.

För att hantera komplexiteten av LCA i byggnader har en undersökning av tillgängliga förenklingsstrategier presenterats. En systematisk sökning och granskning har gjorts av LCA litteraturen. Resultaten visar ett brett utbud av etablerade förenklingsmetoder som följer fem centrala förenklingslogiker: exkludering, datasubstitution, expertbedömning, standardisering och automatisering. Dessa förenklingsstrategier kan användas för att göra LCA lättare att använda i byggnadssammanhang.

År 2022 kommer användningen av LCA-baserade klimatdeklarationer att bli ett statligt krav i den svenska byggsektorn. För att effektivisera användningen av LCA i byggnader räcker det inte att bara tillämpa LCA för att beräkna växthusgasutsläpp av en färdig byggkonstruktion. Om ambitionen är att fullt utnyttja den potential som LCA kan inneha för industri och ekologi så är det nödvändigt att integrera LCA mer aktivt i planering, design och konstruktion av bostadshus.

Nyckelord: Livscykelanalys (LCA), förenklad livscykelanalys, livscykelarbete (LCM), byggnation, flerbostadshus

List of Publications

Part of this thesis is based on the work contained in the following publication:

I. Beemsterboer, S., Baumann, H. and Wallbaum, H. Ways to get work done: a categorisation of simplification practices in LCA. Submitted to *the International Journal of Life Cycle Assessment.*

ADDITIONAL PUBLICATIONS

The following publications are related to the topic but are not part of this thesis:

A. Beemsterboer, S., Baumann, H. and Wallbaum, H. (2019) Integrating LCA in planning, design and construction practices for new multifamily residential buildings in Sweden. Poster presented at the 9th International Conference on Life Cycle Management. Poznan, September 1-4.

B. Koch, C. and Beemsterboer, S. (2017). Making an engine: Performativities of building information standards. Building Research & Information, 45(6), 596-609.

C. Beemsterboer, S. and Koch, C. (2017). A Human Touch: Examining the Roles of Middle Managers for Innovation in Contractors In: Chan, P W and Neilson, C J (Eds.) Proceeding of the 33rd Annual ARCOM Conference, 4-6 September 2017, Cambridge, UK, Association of Researchers in Construction Management, 430-439.

D. Beemsterboer, S., Hallgren, J., Olsson, R., Koch, C. (2017). Too complex to standardise? A case study of a socially loaded pier inspection process at the port of Gothenburg. 9th Nordic Conference on Construction Economics and Organization. Gothenburg, June 12-14.

E. Dijk, M., de Kraker, J., van Zeijl-Rozema, A., van Lente, H., Beumer, C., Beemsterboer, S., & Valkering, P. (2017). Sustainability assessment as problem structuring: three typical ways. *Sustainability Science*, 1-13.

F. Beemsterboer, S. & Kemp, R. (2016). Sustainability assessment of technologies. In *Sustainability Science: An introduction*. H. Heinrichs, P. Martens, G. Michelsen, A. Wiek (eds.). (pp. 71-83). Dordrecht: Springer.

G. Verbong, G., Beemsterboer, S. & Sengers, F. (2013). Smart grids or smart users? Involving users in developing a low carbon electricity economy. *Energy Policy 52*, 117-125.

Contents

Preface

This licentiate thesis has been made possible by a grant from the Development Fund of the Swedish Construction Industry (SBUF) (#13292). The grant was awarded to study the simplification of Life Cycle Assessment (LCA) for residential buildings. To the construction companies involved in the SBUF project, LCA holds a promise of helping to realise environmental sustainability ambitions. At the same time do many experience difficulties in using LCA in their design and construction processes. This licentiate is a response to the challenges of using LCA in the construction industry. I am especially grateful to the LCA analysts and environmental managers for the time and efforts they took to share their ideas and experiences about LCA in the building industry. I hope you find this licentiate useful in making further steps towards adopting a life cycle perspective.

A special thank you is also reserved for the many people that have supported me on this academic path. First and foremost, I would like to thank Holger Wallbaum and Henrikke Baumann for providing me the opportunities to become a better researcher. To have a supervision team that can support all domains of my research is a luxury that I am lucky to have. I am also greatly indebted to Christian Koch who gave me the opportunity to start as a project assessment at Chalmers. Your engagement has been crucial for finding a joyful path into academia. I also want to thank family, friends and colleagues. Thank you for sharing your encouragements, insights and laughter.

Finally, I want to thank Valbona for being a continuous source of inspiration and support. I am looking forward to our next steps in the life cycle.

1 Introduction

Life cycle assessment (LCA) is a methodology used to assess the expected environmental impacts of natural resource use and polluting emissions in a product life cycle. In a world where environmental impacts of human activities threaten the well-being of future generations, LCA can be used in efforts to develop more sustainable ways of being. This licentiate thesis discusses the use of LCA in the building life cycle of new residential buildings.

In Sweden, it is estimated that the built environment accounts for 21% of the country's domestic $CO_{2\text{-eq}}$ emissions (Boverket, 2019a). Adding a massive use of raw materials and energy in the building life cycle, and it becomes apparent that there are plenty of environmental stresses to consider. An interest in using LCA is taking shape at companies in the building life cycle. A survey of environmental managers in the Swedish building sector reported that 32% of the respondents reported to work in organisations which have experience with LCA (Gluch, Gustafsson, Thuvander, & Baumann, 2014). Since 2015, the Swedish Transport Authority has required an assessment of life cycle energy use and greenhouse gas emissions in larger infrastructure projects (Trafikverket, 2015). Also, the Swedish national board of housing, building and planning (Boverket) will require an assessment of life cycle greenhouse gas emissions in the permit process for new multifamily residential buildings as of 2022 (Boverket, 2018; Regeringskansliet, 2019).

In the light of a mandatory introduction of LCA in the building permit process, its current use is rather unassuming. LCA studies of residential buildings are scarce compared to the number of dwellings built each year. Furthermore, LCA remains largely confined to research projects and environmental communication. LCA is seldom used to influence the planning and production of residential buildings in order to improve the environmental profile of the building life cycle. In Sweden, the building sector is judged to be insufficiently mature to set LCA-based requirements in the building life cycle (Malmqvist & Erlandsson, 2017).

It is unclear why exactly LCA is finding a modest uptake in the building life cycle. Some have pointed to the complexity of doing LCA. Interpreting the complexity of LCA as a barrier to effective LCA use has given rise to ambitions to simplify LCA methodology (Liljekow, Rosén, & Tibäck, 2012; Malmqvist et al., 2011). In addition, the building sector itself has been blamed for the slow adoption of LCA. A lack of resources has been identified as a limiting condition to further LCA use (Liljekow et al., 2012). Looking at the historic evidence of LCA use in other sectors of the Swedish industry (Baumann, 1996), the building sector has been relatively late to adopt LCA.

Whether or not the methodology is complex, it is evident that building companies are struggling to make effective use of LCA in the building life cycle. The inability to use LCA effectively is problematic, given the significant environmental impacts that originate from activities in the building life cycle. Moreover, in 2022, a mandatory assessment of life cycle greenhouse gas emissions in the permit process takes effect. Given these developments, it is evident that shying away from LCA is no longer a feasible option. If building companies do not learn to use LCA effectively, then the government-sanctioned introduction of LCA in the permit process risks becoming little more than an additional administrative burden on an already cumbersome building process. On the other hand, if LCA is used effectively, it offers a potential beyond the reduction of environmental emissions. LCA may even unlock a potential for construction companies and other actors to strategically manage resource and energy questions in the building life cycle.

1.1 Aim and objectives

Considering the ambitions to use LCA more often in the building life cycle, this licentiate thesis aims to clarify the conditions that hinder a more effective use of LCA. It addresses whether LCA is too complex to be used effectively, and whether there are other conditions that may require attention. In addition, it examines whether simplification of LCA may be a meaningful way to stimulate LCA use in the building life cycle.

This licentiate will answer the main research question:

- Is the methodological complexity of LCA a justifiable explanation for the ineffective use of LCA in the building life cycle?

The following questions guided different parts of the research process:

1. Which problems characterise the current situation of LCA use in the building life cycle?
2. What makes the application of LCA methodology in the building life cycle complex?
3. Which types of simplification strategies are currently available to LCA practitioners?

1.2 Delimitations

Some restrictions are introduced to the scope of the study. Most important, this licentiate thesis focusses on new multifamily residential buildings in Sweden. This delimitation is relevant in light of the introduction of a mandatory assessment of life cycle greenhouse gas emissions for new multifamily houses in Sweden in 2022 (Regeringskansliet, 2019). Outside the scope of this study are LCAs of infrastructure developments as well as industrial and commercial properties.

Within the building life cycle, the study is delimited to the building process and its actors, especially, construction companies. Larger construction companies fulfil a combination of important positions in the building process, those of contractors, project managers, engineers, and sometimes developers. The sheer size of some of these companies makes them an important stakeholder in the building life cycle. Clients and architects are secondary in this thesis, despite their obvious importance in the building process. Outside the scope of this thesis are the roles of facility management and deconstruction and waste processing.

Despite these restrictions, the research process was characterised by an open attitude towards expertise that lies outside the scope of this thesis. This is especially true for the study of simplification strategies in the LCA community (Paper I). In the outside world, ideas and experiences travel across the boundaries that confine empirical cases and scientific disciplines. It would be irrational not to learn from knowledge that exists beyond the narrow confines of the research object.

1.3 Research design

In order to operationalize these research questions a mix of research approaches were taken. The problems with LCA use in the building life cycle (question 1) and complexity as a specific problem (question 2) have been studied from an academic and an industry angle. A literature-based study explores what is currently known about these questions in the academic building LCA community. To gain access to LCA use in the building industry, an empirical study was performed involving five Swedish construction companies. Experiences from LCA analysts and environmental managers with LCA were explored in an interview-based study and LCA studies were conducted based on the data provided by four construction companies. The accessibility of simplification strategies to LCA practitioners (question 3) was examined using a systematic search and review of the LCA simplification literature.

Table 1 presents an overview of the research methods used to answer the different research questions. It also identifies the chapters of the kappa in which these research questions are discussed. There is an overlap between Chapters 2 and 3 in this licentiate in the sense that they both address question 1 and 2. This overlap is a consequence from the decision to separate the literature-based study from the empirical informed account. This structure allows the reader to distinguish the knowledge already available elsewhere (ch.2) from those accounts that are newly collected in this licentiate (ch.3).

A key conceptualisation in this licentiate are the related concepts of building life cycle and building project. The building life cycle is an LCA inspired concept that includes everything from raw material extraction to final disposal or reuse of resources. The building project includes the activities included in the planning and production of a building. The building project is therefore normally part of the building life cycle. When activities are emphasized, the term building process is used sometimes instead of building project.

Table 1: Overview of methods used in different sections of the licentiate thesis

Questions	*Methods*			*Outline*	
	Literature	Interviews	LCAs	Kappa	Paper
1. Problems with LCA use in building life cycle	X			Ch. 2	
		X	X	Ch. 3	
2. Complexity as a problem in LCA	X			Ch. 2	
		X	X	Ch. 3	
3. LCA simplification strategies	X			Ch. 4	Paper I

1.4 Research methods

The remainder of this introductory chapter details the research methods used and the outline of the licentiate. As described in Table 1, the research methods employed include literature study, semi-structured interviews, and LCA. In this section, a more detailed account is given of the application of these methods.

1.4.1 Literature study

A literature study is used to discuss the problems with LCA use in the building life cycle (question 1) and complexity as a specific problem in LCA (question 2). Following the method of critical review (Grant & Booth, 2009), a narrative analysis provides the reader with key themes concerning LCA use in the building life cycle. It focusses on sustainable development, LCA methodology, building information and organisation, and building LCA research. The ambition is to identify the most relevant concepts without claiming to be exhaustive.

The examination of LCA simplification strategies (question 3) followed a more systematic approach. This review combines a *systematic search and review* (Grant & Booth, 2009) of simplification literature with a *grounded theory informed* analysis (Wolfswinkel, Furtmueller, & Wilderom, 2013). A systematic search of "LCA" and the keywords "simplification", "streamlining", "scoping", and "screening" was conducted on the search engines Scopus and Web of Science. From the analysis, a categorization of simplification strategies was generated. More detail on the application of this methodology can be found in Paper I.

1.4.2 Semi-structured interviews

To better understand the concerns with LCA use for Swedish residential buildings (question 1), an interview-based study was carried out. The study consisted of ten semi-structured interviews with environmental managers and (aspiring) LCA analysts. The interviews centred on experiences with the use of LCA methodology for residential buildings. Special attention was given to perceptions about complexity in LCA of residential buildings (question 2).

Six interviews were conducted with employees in five construction companies in Sweden[1]. The remaining interviews included representatives of an environmental consultant, two clients, and an architect. The interviewees were selected because they expressed an explicit interest in using LCA in their organisation. In four interviews with construction companies, both an environmental manager and a more junior employee were present. The interviews lasted 60 to 120 minutes and were combined with a short presentation of the licentiate research. The interviews with the construction companies and the environmental consultant were taped and transcribed. For the remaining interviews with clients and the architect, notes were taken and worked out after the interview.

1.4.3 LCAs of multifamily residential buildings

Within this licentiate, LCA studies of nine multifamily residential buildings were conducted at four construction companies in Sweden. The data collected in this study is intended to feed into a larger effort to perform a cluster analysis whose results allow for easy application of LCA in the early stages of building projects. The studies presented an opportunity to conduct work together with four construction companies in the building life cycle. It allowed insight into the problems that building companies face when working with LCA (question 1).

The LCA studies were restricted to resources used in the product stage of the building life cycle (A1-3) and the impact category global warming potential (GWP). Generic emission data was used from EcoInvent v3.5. Midpoint impacts were calculated from the inventory results using ReCiPe2016 (H). The functional unit is “one square metre of heated floor area” (HFA, A_{temp}). The construction companies contributed with data on material quantities that make up the bill of resources in the inventory data.

In collaboration with the companies, different approaches were followed to collect the bill of resources. For three studies, a company staff member produced data from a cost calculation

[1] Four companies belong to the six largest construction companies in Sweden based on turnover. The fifth company is significantly smaller but still on the list of thirty largest construction companies in Sweden (Sveriges Byggindustrier, 2018).

programme. In four LCAs, the generation of a bill of resources was initially carried out in master thesis projects (Berglund & Cederbom, 2017; Brandt & Sonesson, 2017; Henriksson & Ulander, 2019). Two of these thesis projects were supervised by the author of this licentiate. One building was included from an unpublished internal company study. One building was based on a building information model (BIM) to which access was granted. For all buildings but one, the subsequent data work required to match the bill of resources with selected inventory emission data was conducted by the author of this licentiate. The one exception is the most detailed study, for which an inventory list was generated in a master thesis project under supervision of the author of this licentiate (Henriksson & Ulander, 2019). In this way a degree of consistency was attempted amongst the different studies.

1.5 Outline

The results of this licentiate are structured according to three content-based chapters followed by a concluding discussion and research outlook. Chapter 2 presents the results from a literature-based exploration of LCA use in the building context. It discusses central problems identified with LCA use for residential buildings and examines complexity as a specific problem to LCA practice. Chapter 3 presents an empirically informed account of the experiences and perceived problems of Swedish construction companies in using LCA on residential buildings. Together, these two chapters give insight into the existing problems with LCA use in the building life cycle, and the perception of complexity as a specific problem. In Chapter 4, the focus changes from the problems experienced in the building sector, to a response to the complexity of LCA. A review of available LCA simplification strategies is presented in paper I. The text in Chapter 4 introduces the origins of simplification debate and gives applications of the simplification strategies for residential buildings in Sweden. Chapter 5 discusses the main findings from this licentiate and presents an outline for future research.

2 LCA use in a building context

Efforts for a more sustainable development are a response to concerns about the environmental and social consequences of human action. The human-induced release of greenhouse gases in the atmosphere drives a change in climate conditions with expected strong negative effects for human well-being (IPCC, 2013). Other critical areas where human activity threatens the conditions for future well-being have been identified as planetary boundaries. Next to climatic stability, human action also threatens the diversity in the biosphere and induces significant land-system changes (Rockström et al., 2009; Steffen et al., 2015). The aim for a more sustainable development follows the realization that environmental concerns are no longer isolated to local events of environmental pollution. Because of our actions, we risk to no longer be able fulfil our common needs (Brundtland, Khalid, Agnelli, Al-Athel, & Chidzero, 1987). While stresses on environmental support systems may be slow and difficult to identify, the gradual weakening of environmental support systems has been identified as a lead cause for the collapse of many civilizations (Ponting, 2007).

In the building life cycle, environmental concerns have been mainly connected to the large amounts of materials and energy needed. In Sweden, the building sector accounts for 21% of greenhouse gas emissions[2], 18% of particle emissions, 37% of energy use, and 31% of waste produced domestically (Boverket, 2019a).

In response to the environmental concerns, a variety of initiatives been launched to create a more sustainable built environment. Environmental certification schemes are used voluntarily in building projects to guide environmental work. Energy declarations are now mandatory in the building process and contribute to a reduction in operational energy in buildings (Boverket, 2009). More ambitious initiatives include a further reduction in operational energy use to reach passive house standards or even reach a positive energy balance (Passivhus IG, 2019). In Sweden, the ambition is to reduce greenhouse gas emissions and reach net zero

[2] The division of greenhouse gas emission between domestic and imported goods is about 60/40. In addition to the 12,8 million tons $CO_{2\text{-eq}}$ produced domestically, the sector accounts for about 8,2 million tons off $CO_{2\text{-eq}}$ through imported goods (Boverket, 2019a).

emissions by 2045. In line with this goal, many sectors have developed roadmaps to transition away from fossil resources (Fossilfritt Sverige, 2018).

2.1 Life cycle assessment

Within the context of sustainability initiatives, LCA suggests a systematic quantification of environmentally relevant flows to assess the expected environmental impacts of goods and services. LCA has a holistic ambition of including all relevant stages in a product life cycle and a comprehensive set of environmental impact categories.

Typically, the LCA procedure is divided into four stages following the ISO 14040 standard (see Figure 1).

- *Goal and Scope: Describe the intended application, audience, and reason for carrying out the study, and define the breadth, depth and detail of a study.*
- *Inventory Analysis (LCI): Collect data on resource use and emissions for individual processes, and quantify an inventory list of all relevant resource inputs and emission outputs in a product system.*
- *Impact Assessment (LCIA): Estimate the potential environmental impacts from the resource and emission flows identified in the inventory analysis.*
- *Interpretation: Explain the results from the LCI and LCIA to identify significant issues and test the robustness of the results.*

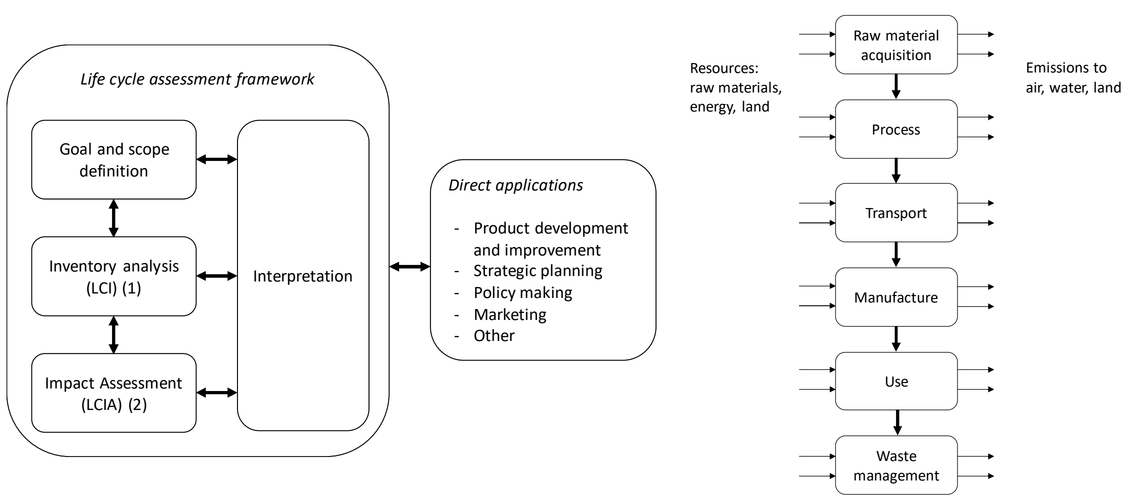


Figure 1: Four stages of an LCA procedure in ISO14040 (ISO, 2006a), and the resulting life cycle model (Baumann & Tillman, 2004)

With this procedure followed iteratively, a life cycle model is created that involves all relevant activities in a product system, as well as the resources used and emissions generated in each activity (Baumann & Tillman, 2004).

While the LCA procedure typically remains the same regardless of the product system studied, the life cycle model is specific to the field of application. Figure 2 gives an overview of the main stages in the life cycle model of a building following the EN 15879 standard (CEN, 2011). Note how many of these information modules bear names of activities in the construction and use of buildings.

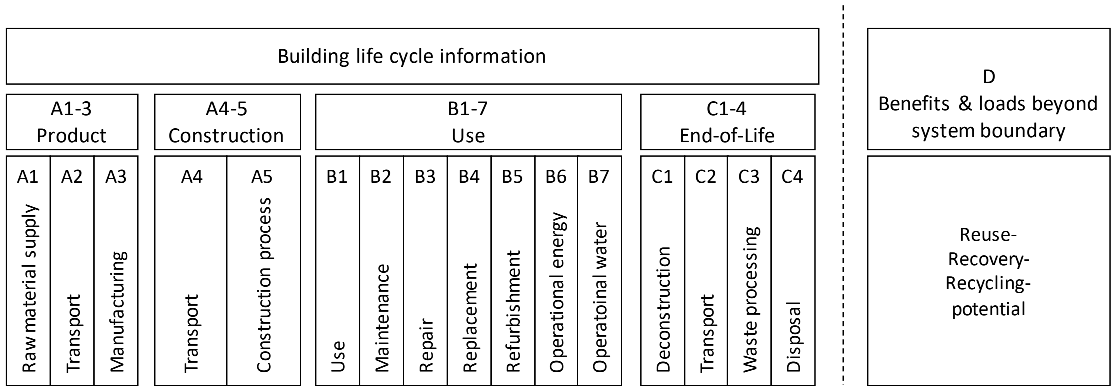


Figure 2: Building assessment information in EN 15879 (CEN, 2011)

The systematic data compilation on relevant resource and emissions flows and their translation to an estimation of expected environmental impacts can be a laborious task. It requires the analyst to map complex product life cycles with processes spread out over many different places. To complicate matters, the use and end-of-life phase in a life cycle model typically belong to a future time. When all relevant activities in a product life cycle have been mapped, the LCA analyst faces the challenge to find and collect data on the resources and emissions that flow from each activity. Furthermore, the conversion of a list of resources and emissions into an estimation of environmental impacts requires the use of methods that model complex damage pathways. Clearly, this is no easy task, and LCA results are often less exact and complete than one may want them to be. However, the systematic compilation and visualisation of the environmental consequences of human action makes LCA an invaluable methodology to inform discussions on sustainable development.

2.2 Structuring building information

To use LCA to assess the environmental performance of a building life cycle requires the structuring of a great deal of information. A standard model for the main activities in a building life cycle has been introduced in Figure 2. However, this model does not provide much information about the building itself.

There are at least three ways of describing a building that have a specific relevance for LCA (see Figure 3). Functional differences can be described between buildings or parts thereof, in order not to compare apples with oranges. It makes little sense to compare a multifamily residential building with a hospital. Even though they may both have rooms and showers, they clearly fulfil different functions. In a similar sense, one may question whether a free-standing single-family house with a garden is functionally equivalent to a dwelling in a multifamily residential building. A functional description of a building is included in LCA in the definition of a functional unit.

Building components describe the main physical parts of building for which inventory data is collected using the EN 15978 framework in Figure 2. Building components separate foundation from roof, and inner walls from outer walls. Building components can have multiple functions, which is a source of confusion when doing LCA. For example, an outer wall insulates a building from outside temperature but may also have a load bearing capacity. In comparison of different product systems, it may be difficult to find functional equivalent systems. Some degree of clarity may be gained by adopting a more disaggregate view on building components, for example by separating the façade from the outer wall. However, no perfect description exists.

Building materials provide the building blocks on which much of the inventory data are collected. Both bill of resources and emission data connect to the building materials used. In a building LCA, an area of interest concerns the relative effects of wooden and concrete-based structural materials (Brandt & Sonesson, 2017; Larsson, Erlandsson, Malmqvist, & Kellner, 2016; Peñaloza, 2016). Another group of materials where LCA has sparked interest are thermal insulation materials (Kono, Goto, Ostermeyer, Frischknecht, & Wallbaum, 2016). While typical insulation materials are mineral or oil-based, it may be environmentally attractive to consider alternative insulation materials such as hemp (Andersson & Björkhagen, 2018).

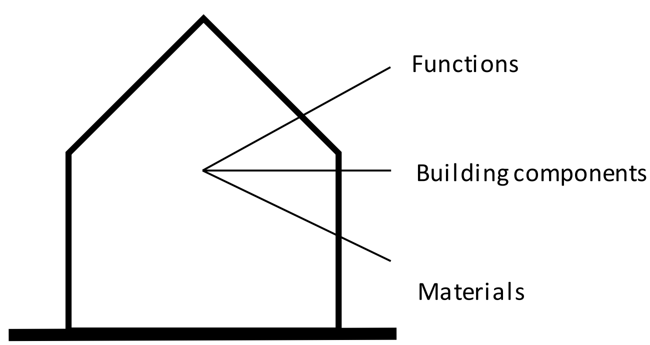


Figure 3: Building perspectives with relevance for LCA

A possible fourth way to structure building information – besides functions, components, and materials – is to distinguish between different systems or layers in a building (Berge, 2009; Brand, 1994). Systems may be useful identify functional and other requirements for building components and materials. The separation of a building into different systems can be used to guide material selection in the building design process (Meex, Knapen, & Verbeeck, 2016). This can be done by making explicit the different time-frames of systems and particular materials in a building (Berge, 2009). While a typical functional unit includes a 50- to 60-year building service life, the site work and structure of a building should normally last longer. The façade (skin) of a building and services may not last as long, and mobile equipment typically only last five to ten years. LCA studies centre mainly on the structure, skin, and space plan. Scarce are studies of services, mobile equipment and site excavation.

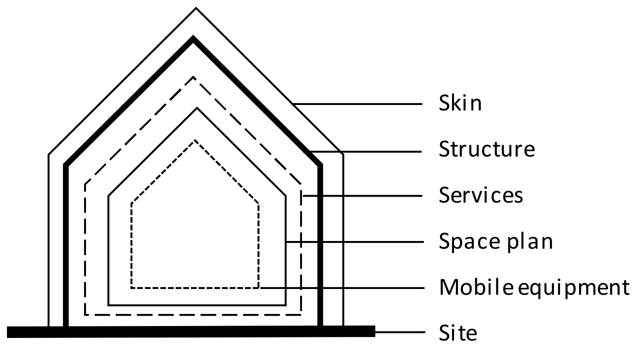


Figure 4: Layers or systems of a building (adapted from Brand, 1994; Meex et al., 2016)

There are different ways to structure building information in LCA, and the presented options are certainly not exhaustive. For example, different scale levels may influence the way information is collected. On a more detailed level, is LCA can be used to assess building material and components in developing environmental product declarations (EPDs) (Ortiz, Castells, & Sonnemann, 2009). A recent trend is to use LCA on a more aggregate level to assess neigboorhoods (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015).

The preference for a specific information structure is not merely a research interest. The way in which information is structured can have an influence on the final building design. Different information structures can be seen to benefit different stakeholder groups in the building process (Koch & Beemsterboer, 2017). A well-established information standard in the Swedish building sector is BSAB96. The newly developed CoClass information standard attempts to replace BSAB96 (Svensk byggtjänst, 2019). Ironically, the recently released BM1.0 building climate calculation tool relies on the older BSAB83 standard (Erlandsson, 2018b). Also, many design and cost-calculation programmes have their own information structure, which do not have to connect with the chosen information structure in the inventory model.

2.3 Building project and its actors

So far, the presentation of building LCA has been confined primarily to the technical aspects of the building life cycle. Restricting LCA to the technical aspects of a building works well to account for physical flows of resources and emissions. However, it fails to account for the people involved in a building life cycle. Buildings do not simply happen: they are designed and constructed by people who work for companies in a building project. A populated version of

LCA recognises the importance of the people and organisations involved in a life cycle (Baumann, 2012). If LCA is to be used effectively, it seems appropriate to acknowledge the people and organisations that are part of the building life cycle.

A central organising principle in the building industry is the building project (Dubois & Gadde, 2002; Hansson, Olander, Landin, Aulin, & Persson, 2015; Winch, 2010). The building project is a temporary constellation of stakeholders who work closely together. A classical depiction of a building project consists of a planning stage, a design stage, and a construction stage. In the planning stage, ideas of the building's requirements are described in the project brief. Based on the requirements set in the project brief, a first concept of the building is drawn. The client and architect are typically regarded the most important actors in this stage of the process. Based on the initial drawings, further details of the building design are worked out. In this process, the role of engineering disciplines tends to increase. The architect finalises a floorplan in collaboration with the client and the structural engineer. Structural engineers design a technically sound load-bearing system and building envelop that meets the requirements from the brief and concept drawing. Other engineering specialist come in to design solutions for a range of issues such as heating, ventilation and air conditioning (HVAC), sound insulation, and fire-safety. In the construction stage, the physical construction of the building is organised by a contractor. Typically, the contractor sub-contracts part of the construction activities to more specialist sub-contractors. The resulting picture of a building project resembles that described in Figure 5.

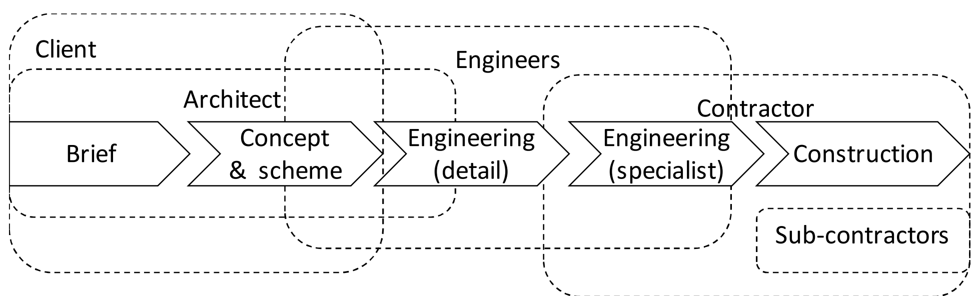


Figure 5: Typical stages in a building project and the most relevant actors (Gray & Hughes, 2001)

This classical image of a building project has in recent years undergone modifications with relevance for a life cycle approach. First, some descriptions of the building process now also include the operational stage (Hansson et al., 2015). An active consideration of the operational stage raises the possibility of taking into account choices related to energy efficiency (Nägeli, Farahani, Österbring, Dalenbäck, & Wallbaum, 2019), and maintenance and renovation measures (Farahani, 2019). Second, the deconstruction activities at the building's end-of-life stage may also be considered part of the building process (Hansson et al., 2015). Including the end-of-life stage opens up the building project to consider to more active considerations of material reuse through design-for-deconstruction (Guy, Shell, & Esherick, 2006).

With the inclusion of operational and end-of-life stages, the extended building process starts to look more like the building life cycle in Figure 2. However, there remain crucial differences between the building process and the building life cycle. In the building process, a planning and design stage is crucial in shaping the building and its environmental impacts. In the building life cycle, planning and design are usually excluded because the design activities themselves account only for a minor part of environmental impacts. Instead, the building life cycle prioritises the impacts from mining, transport, and manufacturing of building materials and products. In the building design process, these supply-chain activities are usually not explicitly considered.

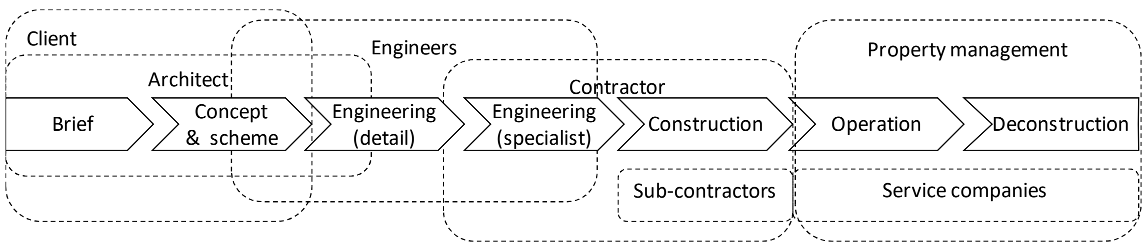


Figure 6: Stages in an extended building project and the most relevant actors

While the importance of building projects is well established, it does not stand alone as an organisational form in the building industry. However, because people work only temporarily on a building project, a more permanent organisational form has developed alongside the building project. While architects and engineers work on building projects, they are typically permanently employed by companies in the building sector. The building process contains therefore both a company coordination and project coordination (Winch, 2010).

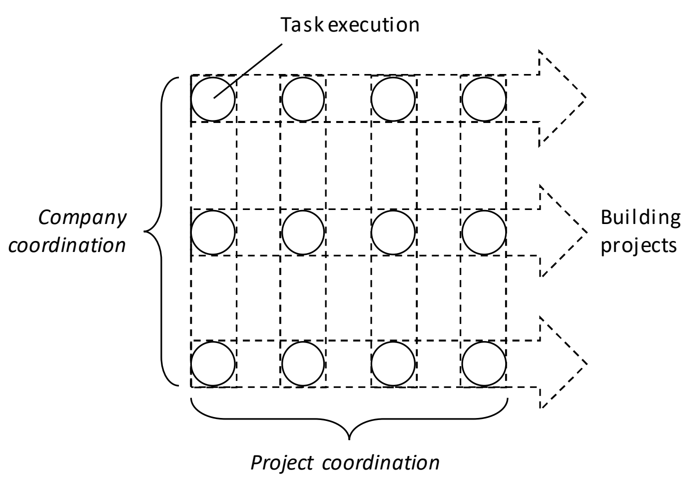


Figure 7: Tension between the company organisation and the project organisation (Adapted from Winch, 2010)

Because of different goals and time perspectives, a tension can emerge between a building project and the building company (Figure 7). Differences between project organisation and company organisation have been identified as a limiting factor for environmental work in the construction sector. Most environmental work is organised around company-centred activities, whereas most environmental impacts are actually generated in building projects (Gluch, 2005).

2.4 Drivers and barriers to LCA use in residential buildings

In residential buildings, early applications of LCA were strongly driven by an interest in optimising total primary energy demand. Early studies showed that around 80% of energy used in the life cycle of residential buildings was connected to operational energy demands from space heating, hot water, and electricity use (Adalberth, 1997; Gielen, 1997). With improved insulation of buildings, the share of operational energy gradually decreased, giving rise to a more active consideration of embodied energy from construction materials. In recent studies, a climate change focus has become more important to assess multifamily residential buildings in Sweden (Larsson et al., 2016; Liljenström et al., 2015). On a material level, ambitions to use more wood in construction have driven LCA studies of wood-based construction techniques (Brandt & Sonesson, 2017; Larsson et al., 2016; Peñaloza, Erlandsson, & Falk, 2016). Together, the consideration of energy use, climate change, and wood-based construction techniques have been drivers for LCA in the building life cycle in Sweden.

However, compared with many other sectors, the demand for LCA studies on residential buildings is relatively small (Malmqvist et al., 2011; Zabalza Bribián, Aranda Usón, & Scarpellini, 2009). A reason for the limited demand is the voluntary nature of LCA and related assessment tools (Cole, 1998; Zabalza Bribián et al., 2009). The introduction of legal obligations can stimulate LCA use (Boverket, 2016; Zabalza Bribián et al., 2009).

More reasons are given in the LCA literature to explain the limited use of LCA in the building life cycle. A shortage of resources hinders effective LCA use. Key resources identified include time, money, ability, and data availability (Lewandowska, Noskowiak, Pajchrowski, & Zarebska, 2015; Malmqvist et al., 2011). LCA is a data-intensive practice. Different authors have expressed the difficulty of getting enough and sufficiently high-quality inventory data (Malmqvist et al., 2011; Ramesh, Prakash, & Shukla, 2010). Data is perceived to be especially scarce in the early design phase of a building project, where the opportunity for change is typically largest (Malmqvist et al., 2011, pp. 1901-1902).

Concerns about the accuracy and consistency of LCA also hinder effective LCA use. Uncertainty in a building LCA is inevitable because of large amounts of measured and simulated data and simplified modelling of complex environmental cause-effect chains. The challenge becomes one of finding acceptable levels of uncertainty (Hellweg & Mila i Canals, 2014). Increasing the accuracy and consistency of studies is of interest because it enables a comparison between buildings (Cole, 1998; Malmqvist et al., 2011).

Another barrier to LCA use is a perceived lack of understanding of and experience with the methodology (Zabalza Bribián et al., 2009). LCA is persistently recognised as complex in publications (Lewandowska et al., 2015; Malmqvist et al., 2011; Zabalza Bribián et al., 2009). While it is recognised that the perception of complexity may hinder the use of LCA (Malmqvist et al., 2011; Zabalza Bribián et al., 2009), it is worthwhile to examine which aspects of a building LCA may genuinely introduce complexity.

2.5 Complexity in residential building LCAs

A colloquial way of expressing complexity is to refer to aspects that are complicated to understand. A more scientific understanding of complexity centres on non-reductionism, the idea that an issue at hand cannot be reduced to its separate parts (Simon, 1962). Complex systems have been described as non-linear, emergent, containing multiple perspectives, and with interaction effects outside the system (Ramage & Shipp, 2009). Sources of complexity include: a large number of variables (Klir, 1991), value differences (Rittel & Webber, 1973), interaction effects and technology evolution (Sandén, 2004; Sandén & Karlström, 2007), different time dimensions (Hillman, 2008), and a general difficulty in containing an issue within closed system boundaries (Churchman & Churchman, 1971). A complicated system is therefore not the same as a complex system. What is considered complicated lies very much in the eye of the beholder, whereas complexity is more a characteristic of the system itself.

In this section, six sources of complexity in building LCA are discussed: system volume, system variability, system interaction, subjective interests, time, and geography. Subsequently, for each source of complexity, building-specific and LCA-specific sources are considered. An overview of these issues is presented in Table 2. Note that system volume and variability are technically not sources of complexity. They are included because they contribute to the general perception of a building LCA as complicated to conduct.

System volume refers to the scale and size of a system. Buildings consist of a high number of materials and processes which complicate comprehensive assessment (Buyle, Braet, & Audenaert, 2013; Cole, 1998; Ramesh et al., 2010). Buildings consists of different sub-systems, each of which works according to a different logic. Similarly, LCA methodology is characterised by the compilation of emissions and resources and the quantification of these flows into a host of environmental impact categories (Glaumann et al., 2010; Hellweg & Mila i Canals, 2014).

System variability emphasises the uniqueness and difference between parts of a system. In a building LCA, the unique character of each building is often emphasised (Buyle et al., 2013; Kotaji, Schuurmans, & Edwards, 2003; Ramesh et al., 2010; Rossi, Marique, Glaumann, & Reiter, 2012; Zabalza Bribián et al., 2009). Aspects such as function (Rossi et al., 2012), design (Kotaji et al., 2003), and materials used (Ramesh et al., 2010) make buildings unique. The differences between building projects make it more attractive to conduct new LCA studies.

Methodological variability in LCA goes back to the early days of environmental assessment, when each actor had one's own performance indicators and benchmarks (Cole, 1998). While a degree of harmonisation has taken place, there persists a confusing variety in LCA methods, databases and standards.

Table 2: Sources of complexity in building LCAs

Category	*Building-object-specific*	*LCA-methodology-specific*
System volume	Many building products, materials	Emissions, resources, impacts categories
System variability	Unique building project, different building systems	Different methods, databases, standards, etc.
System interaction	Aggregate effects	Second-order effects
Subjective interests	Stakeholders, professional disciplines	Subjective methodological choices, goal dependent choices
Time	Design process, building life time, variable life time for components, changes in form and function, technological evolution	User scenarios, recycling potential, damage pathways, methodological learning, data obsolesce
Geography	Site, climate, solar insolation	Transport distances to site, regional differentiation in environmental impacts, land use change

System variability emphasises the uniqueness and difference between parts of a system. In a building LCA, the unique character of each building is often emphasised (Buyle et al., 2013; Kotaji, Schuurmans, & Edwards, 2003; Ramesh et al., 2010; Rossi, Marique, Glaumann, & Reiter, 2012; Zabalza Bribián et al., 2009). Aspects such as function (Rossi et al., 2012), design (Kotaji et al., 2003), and materials used (Ramesh et al., 2010) make buildings unique. The differences between building projects make it more attractive to conduct new LCA studies. Methodological variability in LCA goes back to the early days of environmental assessment, when each actor had one's own performance indicators and benchmarks (Cole, 1998). While a degree of harmonisation has taken place, there persists a confusing variety in LCA methods, databases and standards.

System interaction introduces complexity in the form of second order effects. Second order effects are introduced through feedback loops (Ramage & Shipp, 2009). In buildings, these are sometimes referred to as aggregate effects and may result from the interaction between different sub-systems (Cole, 1998). The interaction of sub-systems in buildings affects overall building performance (Abel & Elmroth, 2008). Interaction between sub-systems can be introduced through design changes, and have been shown to complicate building LCA (Ylmén, 2017).

Different *subjective interests* and preferences exist among different stakeholders in the building life cycle. In a building project, this is evident from the many stakeholders that are involved (Kotaji et al., 2003). Client, architect, subcontractors, purchasing, and management are but a few of the stakeholders in a building project. Each of these actors comes with individual preferences (Cole, 1998). In LCA, subjective differences are introduced through subjective methodological choices. Subjective methodological choices are an explanation of the differences between LCA results (Säynäjoki, Heinonen, Junnila, & Horvath, 2017).

Time contributes to complexity in a building LCA in multiple different ways. Buildings are typically characterised by a life span of 50 years or more (e.g. Buyle et al., 2013; Kotaji et al., 2003; Rossi et al., 2012; Zabalza Bribián et al., 2009). Typically, longer life spans increase uncertainty in assessment (Buyle et al., 2013). Overall, future developments may be difficult to predict. The building may change form and function during its life span (Kotaji et al., 2003; Zabalza Bribián et al., 2009), for example through maintenance and retrofitting (Buyle et al., 2013). Different building components have different life spans (Buyle et al., 2013). Technologies may change in unknown ways. In LCA of building design projects, this is an important consideration given that the operational phase of a building is a prime contributor to total life cycle impacts. An additional time related issue may be the shortage of time to carry out an assessment. LCA may have the highest influence in earliest design phases, when the available knowledge is smallest (Malmqvist et al., 2011).

Conditions of *geography* contribute to the complexity of a building LCA. The characteristics of a building site contributes to the perceived uniqueness of building designs. For example, climatic conditions and solar insolation differ depending on a building's location (Zabalza Bribián et al., 2009). In the compiling of an inventory list, different transport distances between factories and the building site may be difficult to estimate (Buyle et al., 2013). Regional differentiation in environmental impacts complicates life cycle impact assessment. Currently, more space sensitive categories such as land use change are typically disregarded in building LCA (Allacker, Souza, & Sala, 2014).

The distinctions between building-object-specific and LCA-methodology-specific sources of complexity show that the sources are not unique to either category. This is an important finding, as it may help building actors appreciate that the sources of complexity in LCA are not essentially different from those tackled successfully elsewhere in a building process. LCA may be difficult to understand, but this does not mean that it is more complex than building a residential building.

In addition, it is evident that there are other problems with performing LCA in the building project. A lack of demand, resources, data availability, and competences are but some of the other aspects that hinder the effective use of LCA. Based on the literature discussed, it is difficult to maintain that the complexity of LCA may be held accountable for the ineffective use of LCA in the building life cycle.

3 Insights from Swedish construction companies

This chapter presents an empirical account of experiences with LCA of multifamily residential buildings at five construction companies in Sweden. Experiences from (aspiring) LCA analysts and environmental managers are explored through interviews and LCA studies. This chapter provides an empirically informed account for the research problem discussed in Chapter 2. Following an abductive logic (Alvesson & Sköldberg, 2009), Chapters 2 and 3 together inform the examination of the research problem.

3.1 Experiences from doing LCA with data from building companies

In the context of this licentiate, nine LCA studies were conducted together with construction companies of concrete-based multifamily houses in Sweden. The LCA studies provide an additional context in which to reflect on the issues voiced by environmental managers and LCA practitioners in the interviews.

The estimated emissions of the analysed multifamily buildings fall between 120 and 380 kg $CO_{2\text{-eq}}$ per m^2 HFA. These estimations do not dramatically differ from the 214 to 350 kg $CO_{2\text{-eq}}$ range found in recent LCAs of Swedish concrete-based multifamily houses[3] (Erlandsson et al., 2018; Erlandsson & Pettersson, 2015; Liljenström et al., 2015). The range is logically smaller than the -7 to 637 kg $CO_{2\text{-eq}}$ range found in a comparative analysis of a larger variety of residential buildings in Europe (Birgisdottir et al., 2017). It is also smaller than the 3 to 770 kg $CO_{2\text{-eq}}$ range found in a study including different building types (Säynäjoki et al., 2017).

The results plotted in Figure 8 show that it is difficult to discern any obvious relation between the estimated global warming potential (GWP) and building-object-specific variables such as

[3] Results for other recently published LCA studies report respectively; 302-315 (Erlandsson & Pettersson, 2015), 214-279 (Erlandsson, Malmqvist, Francart, & Kellner, 2018), and 350 kg kg$CO_{2\text{-eq}}$ / m^2 HFA, Atemp (Liljenström et al., 2015) for the A1-3 stage in different concrete-based multifamily houses in Sweden. Note that these studies have used emission inventory data from the IVL Swedish environmental institute, sometimes complemented with primary data from material suppliers.

heated floor area and number of floors. This is not obvious, as one would expect to find efficiency benefits in larger building projects.

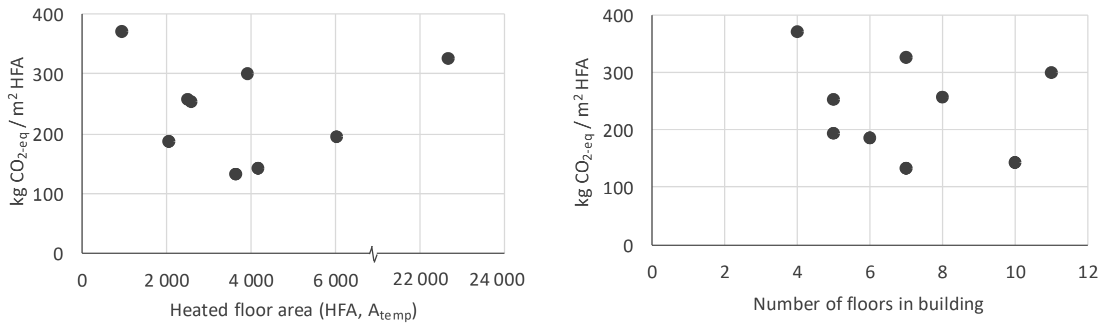


Figure 8: Plotting of LCA results in relation to the building-object-specific variables of building size in heated floor area and building height in floors

Figure 9 suggests that access to a more detailed bill of resources contributed to a higher GWP in the LCAs. Four buildings with the lowest GWP are also the buildings with least detail in the bill of resources and the fewest types of inventory data collected. In these studies, the collection of data to compile the bill of resources was conducted by a company employee without prior experience with LCA. This led to a data retrieval of about 40 aggregations in the bill of resources, to which fewer than 15 types of emission data could be connected. For this reason, the lower values should be treated with suspicion as they may well be a result of limitations in the LCA study.

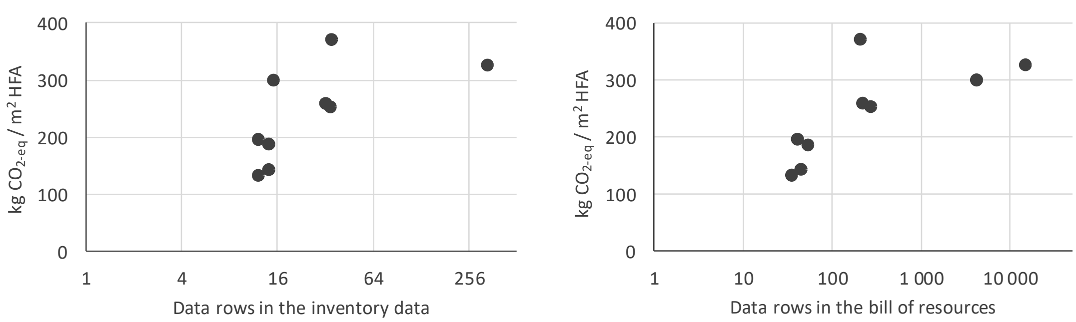


Figure 9: Plotting of LCA results in relation to study specific indicators of data quality expressed in number of data rows in inventory emission data and the inventory bill of resources

It seems that there is a threshold above which more detail no longer increases the total emissions. In one study, a BIM-based drawing allowed a high level of detail for a limited amount of building materials (4 000 rows in bill of resources, 15 inventory materials selected). In another study, a partnering contract form gave access to a highly detailed account of the type of materials used in a building (14 000 rows in the bill of resources and 332 materials selected as inventory data). Based on these results, it is not possible to conclude that a drastic increase in detail in the LCA further increases the total emissions of the building. It seems that the total emissions level off after the inclusion of about 200 inputs in the bill of materials and the selection of about 30 inventory emission data sets.

A comparison of the results plotted in Figure 8 and Figure 9 indicates that the level of detail in which LCAs were conducted is more relevant to the calculated emissions than building object specific variables such as heated floor area or number of floors. The importance of methodological choices for explaining differences between LCA studies has been emphasised previously in a larger and more systematic comparative analysis of building LCA (Säynäjoki et al., 2017). Without discarding other relevant parameters such building weight, it is important to be attentive to the influence of methodological choices on calculated emissions in LCA. Choosing an appropriate level of detail in an LCA study is an example of such a choice.

In this context, it is evident that a more detailed and comprehensive study is not always preferable to a more limited study. Increasing the scope or level of detail in a study typically increases the amount of data to be compiled. In most of the LCAs presented, the work to compile a bill of resources turned out to be more time-intensive than anticipated. There were, however, large differences in the time spent on collecting the inventory data. In the less detailed studies, an experienced cost estimator could provide a restricted bill of resources in about 12 hours. In the most detailed study, it took about three weeks to compile a bill of resources for Stage A1-3.

Subsequent activities to convert the data to a form useful for LCA analysis and find a matching emission inventory dataset typically took a similar amount of time. Data work in LCA typically involves a significant deal of manual work. The core of this work lies in transforming the data to match with the available emission data. Table 3 gives an overview of the types of data work that are involved in compiling a bill of resources that matches the emission data available. Note that several of these steps depend on the analyst's judgement and benefit therefore from experience and expertise.

Table 3: Transformation steps that may involve manual data work in the LCA studies

Transformation steps	
Type A	Sorting information
Type B	Summarising information
Type C	Assumptions regarding size and geometry
Type D	Assumptions regarding material composition
Type E	Calculations of mass or volume
Type F	Calculation of material composition
Type G	Choice of reference material

Source: (Henriksson & Ulander, 2019)

From the LCAs that were conducted with data from the building companies it became apparent that the data work involved in doing LCA can be time intensive. This may give an incentive to reduce the detail of the LCAs.

3.2 Experiences from practitioners in residential building LCA

In addition to the LCAs carried out with data from the building companies, interviews were conducted to gain access to the experiences and understanding of LCA practitioners and environmental managers. The interviews portrayed an image of a context in which there is interest in LCA but also complications in using LCA. Environmental certification schemes such as BREEAM, LEED, Miljöbyggnad and Svanen are leading instruments for building more environmentally friendly. Because several certification schemes have started to give points for use of Environmental Product Declarations (EPDs) and LCA, these schemes stimulate an interest in LCA. Two organisations have operational LCA expertise internally. In most companies, LCAs are restricted to the commissioning of student theses and research projects. A typical goal with an LCA study is to become acquainted with the methodology and account for the $CO_{2\text{-eq}}$ emissions of one or two buildings. Another common activity is the collection of EPDs from material suppliers. Only one organisation claims to use LCA to calculate GWP of building projects on a frequent basis.

While current use of LCA is mainly restricted to individual buildings, most interviewees at the construction companies expressed a desire to use LCA to compare multiple buildings with one another. Furthermore, LCAs are typically only performed after the building design is completed because of the unavailability of inventory data earlier in the building process. Most interviewees also expressed a desire to use LCA early in the planning and design phase. Other pathways for LCA development include a more automated and standardised practice, including integration with calculation tools. From an organisational perspective, several interviewees expressed a desire for a knowledgeable client that can set demands for LCA and make use of its results.

During the research project, two important tools for doing LCA became available to actors in interviewed companies. In 2017, the Swedish Environmental Research Institute (IVL) released a free climate calculation tool for buildings (BM1.0). In the same year, the Finish company Bionova Oy was reported to more actively market the OneClick LCA software tool they developed. One organisation uses the customised LCA tool ANAVITOR. ANAVITOR allows for a direct coupling between economic calculations of material quantities and the IVL environmental database.

3.3 Problems with LCA use

Based on the interviews, the most widely perceived problem is the lack of demand for LCA studies. Construction companies build for clients and perceive that the clients should set explicit requirements or otherwise demand LCA. This can be perceived as doubly problematic if the client does not know what requirements to set. Another explanation for the low demand is the cost of doing LCA.

When LCA is applied, interviewees reported data work as an area of concern. Several analysts experienced a lack of available inventory data. To generate one's own inventory data is considered extremely time-intensive. In the collecting of the inventory data, the generation of a bill of resources was unexpectedly also a source of concern. To an outsider, it may seem strange to think that it is difficult to retrieve a list with material quantities in a construction company. However, this was a practical problem perceived by several interviewees. LCA analysts depend for information on other actors like structural engineers, architects and cost estimators. It was indicated that these actors do not prioritise the work required to share data with the LCA analysts. Furthermore, the collected data can be structured very differently. This leads to concerns for double counting as well as missing out on data.

In the rare cases when an LCA study was demanded, the outcomes generally did not lead to the implementation of more environmentally friendly solutions in a building project. One important reason for this is the timing of the study. Typically, the collection of inventory data is conducted only after the building design has been completed. LCA results then come in too late in the building process to make any meaningful change. Furthermore, the accuracy and consistency of LCA results are questioned. One interviewee expressed concern that LCA knowledge can be difficult to defend when confronted with the everyday pressures of the building site. Almost all interviewees expressed a desire for consistent and comparable results.

Another area of concern is the ability to build up and maintain a workable level of LCA expertise on residential buildings. One organisation lost previously existing LCA competence because of an internal migration of employees to an infrastructure department[4]. Another organisation reported being unable to keep analysts working on LCA for longer than a year. In this respect, it should be noted that the prospect of building up expertise cannot be seen as separate from the ability to use LCA in a meaningful way. Logically, organisations with most regular application of LCA also have the best conditions to maintain qualified analysts.

[4] In Sweden, the application of LCA in infrastructure projects benefits from requirements on LCA set by the State Road Authority (Trafikverket).

3.4 Perceptions of complexity

In line with an interest in the complexity of LCA, the interviewees were asked to reflect on what they perceived to be difficult about doing LCA. A summary of their answers is given here, structured according to the six types of complexity described in Chapter 2.

System volume contributed to perceptions of complexity primarily through the large amounts of inventory data required. On the emission side, the interviewees focussed almost exclusively on $CO_{2\text{-eq}}$ emissions. This significantly reduces the complexity of doing LCA.

System variability was considered problematic when it comes to data work. Relevant inventory data were spread out throughout the organisation and not always available in the same format. Furthermore, one interviewee pointed out that the number of tools available for carrying out LCA led to confusion.

System interaction was not considered a problem given the current state of LCA use on residential buildings. If more advanced LCA studies are conducted in the future, this issue may well resurface.

Subjective interests were a clear source of complexity identified in the interviews. Several interviewees expressed that it may be difficult to meet multiple actors with different demands. The client and the municipality were identified as important external actors. In addition, different interpretation of standards was perceived to increase the complexity of performing LCA.

Time appeared also as a source of complexity in construction companies performing residential LCA. LCA and the inventory data is often available only after a building design is completed. This was perceived to make the realisation of environmental ambitions more difficult.

Issues of *geography* were not explicitly mentioned in the interviews. Geographic issues may become apparent, though, if more advanced LCA studies are conducted. Different climatic conditions do already play a role in the setting of energy requirements for residential buildings. In LCA, the different geographic system boundaries of life cycle inventory (LCI) data may become relevant. Because the interviewees focussed almost exclusively on $CO_{2\text{-eq}}$ emissions, it is unlikely that a regional differentiation of impacts will be of interests in the near future.

3.5 Lessons learned

The insights from the construction companies confirm that there is an interest in applying LCA to residential buildings. At the same time, they support the notion that construction companies do not use LCA effectively. Experience and expertise in LCA on residential buildings are limited in most companies. LCA enthusiasts face a lack in demand for LCA studies aside from thesis- and research projects. Even if LCA is not more complex than many other activities in building, it is still a new methodology to learn and use, and learning can be difficult.

Previous research has stated that complexity of LCA is based on prejudice among architects and engineers (Zabalza Bribián et al., 2009). Here I would like to nuance that statement. The research presented in Chapters 2 and 3 shows that LCA practitioners encounter a wide range of difficulties in applying LCA, of which complexity is only one. A lack of demand, legal standing, resources, data, expertise, and continuity frustrate the learning process and may make LCA more difficult to understand than strictly necessary. If many practitioners find LCA complex, this may not be because of their own prejudice. Instead, it should be considered that LCA is difficult to understand because it is attempted in an unsupportive context.

4 Opportunities for simplifying the application of LCA methodology

Having previously discussed the problems resulting in an ineffective LCA use in the building life cycle, this chapter focusses on a response to the complexity of LCA. Simplifications provide opportunities to reduce the complexity of a task in order to get work done (Star, 1983). A systematic search and review have been conducted of existing ways to simplify LCA work.

4.1 Origins of the simplification debate

A simplification discussion in the LCA community arose in the 1990s. There were concerns that LCA was too complex to be used routinely, despite apparent developments in LCA databases, standards, and software packages (Graedel & Lifset, 2016). In 1995, the United States Environmental Protection Agency (EPA) hosted a conference to discuss simplification strategies in LCA (Curran & Young, 1996). High-profile publications followed from SETAC Europe and North America working groups, as well as a book by Thomas Graedel (Christiansen, 1997; Graedel, 1998; Todd & Curran, 1999). These works showcased somewhat different styles of simplifying LCA using the vocabulary of streamlined LCA.

The streamlining conference report (Curran & Young, 1996) provides insight into some of the main initial ideas about simplification in the LCA community. Streamlining was presented as necessary to speed up LCA for use in (internal) industry and government decision-making. Three general approaches were discussed during the conference: an increase in data availability, a reduction of what is considered in the inventory phase, and a reduction of the impact categories studied. Weitz and colleagues introduce an overview of seven major streamlining techniques used in practice (Weitz, Todd, Curran, & Malkin, 1996). Graedel suggests matrix LCA as an alternative streamlining method. Overall, it was recognised that no single streamlining technique would fit all and that preferences may be shaped by the context of the study (Curran & Young, 1996). Some of these approaches were subsequently developed further and will be discussed later.

In a report drafted by the SETAC Europe working group, Christiansen et al. distinguish between screening LCA and streamlined LCA (Christiansen, 1997). In their publication, streamlined LCA consists of a three-step process. Screening LCA is the first step in a streamlined LCA in which the most relevant parts of the life cycle are identified. The results of the screening LCA should be used to simplify the LCA by identifying parts of the product system under study that can be excluded or where generic data suffices. Finally, the reliability of the simplification should be assessed (Christiansen, 1997). According to Christiansen, the LCI phase in LCA is most commonly simplified because of its data intensive nature and subsequently high opportunities for reducing the time spent on LCA. Data gaps should preferably be filled by using surrogate data such as calculated data or data of similar products (Christiansen, 1997). Notably, Christiansen proposes a hierarchy of simplification strategies that places data substitutions above exclusions strategies.

Graedel introduces an LCA approach based on expert judgement, an approach called matrix LCA. This approach covers all relevant life cycle stages and environmental stressors, like extensive LCA studies. However, instead of compiling an inventory list, matrix LCA uses expert judgements to grade the importance of each stressor in a life cycle stage. The underlying argument is that a good qualitative assessment of all relevant life cycle stages and impacts is preferred over compiling only those flows that can be quantified (Graedel, 1998).

A second SETAC report was published by a North American working group two years after the European version (Todd & Curran, 1999). Streamlining methods discussed include exclusion of certain stages of the lifecycle, processes, or impact categories, the use of 'show-stopper' criteria, and surrogate or qualitative data (Todd & Curran, 1999). Contrary to the European SETAC report, Todd et al. offer no any specific screening or scoping discussion but instead focus on questions that can help determine how much space there is for streamlining. It is not unimaginable to end up with a one stage and impact category LCA based on generic data (Todd & Curran, 1999).

A comparison of the different contributions shows that the authors agree that a complete LCA is impossible to conduct because of real-world limitations in time, cost and data resources. Simplifying LCA becomes a response to limitations in resources. A guiding theme is the desire to reduce data collection efforts. Data collection is perceived as time-consuming, especially when the generation of primary data is attempted. The value of exclusion and data-focussed streamlining techniques is underpinned in all reports.

Table 4 provides an overview of common simplifying techniques addressed in these streamlining publications. This table supports the summary from the EPA conference (Curran & Young, 1996) that exclusion and data strategies are central in the early LCA simplification discourse.

Table 4: Common streamlining techniques suggested in the LCA community during the 1990s

	Weitz, 1996; Curran and Young, 1996	Christiansen et al., 1997	Graedel, 1998	Todd et al., 1999
Exclude (parts of)				
Life cycle system	X	X	X	X
Processes		X	X	
Impact assessment	X	X	X	
Impact categories	X	X	X	X
Inventory parameters	X		X	X
Interpretation		X	X	
Insignificant factors (threshold levels)	X	X	X	X
Common factors		X		X
Data				
Use surrogate data	X	X	X	X
Qualitative data	X	X	X	X
Other techniques				
Use showstoppers			X	X
Matrix methods	(X)		X	
LCIA method development		X		X

A source of disagreement amongst the publications is the degree to which a streamlined LCA should resemble a traditional LCA. The two SETAC work groups promote exclusion and use of surrogate data to produce simplified LCA that largely resemble a normal LCA in form. Christiansen et al. structure the streamlining procedure to emphasise the reliability of the streamlined results. This way of simplifying LCA resembles ISO-based LCA in which exclusions are based on a sensitivity analysis of full results (ISO, 2006b). Todd et al. emphasise the freedom of the practitioner and investigate how much space for streamlining there is. With matrix LCA, Graedel promotes a more radical alternative in which qualitative judgement translates to a life cycle method that emphasises expert judgement over quantification.

In the decades that followed the EPA conference, LCA matured into a dominant environmental assessment methodology with branches into many sectors and domains. With an eye on the impressive developments in the LCA community, it seems timely to examine whether simplification strategies have evolved as well.

4.2 Simplifying logics and simplification strategies

In this licentiate, a systematic search and review of existing simplification techniques has been conducted. The results of this study are presented in Paper I.

The paper gives evidence of a large variety of simplification practices in the LCA community. Ironically, the existence of many simplification techniques may make simplification in LCA a difficult topic to untangle for aspiring LCA analysts. To aid practitioners, an empirically grounded grouping of simplification practices has been developed. This resulted in the identification of 11 simplification strategies following five underlying simplification logics: exclusion, inventory data substitution, qualitative expert judgement, standardisation, and automation. Paper I gives a full account of the simplifying logics and simplification strategies identified.

The presented categorisation is intended for practitioners to better understand and decide upon simplifying LCA practices. The remainder of this chapter supports that goal by illustrating the simplification strategies with examples from building LCA.

4.3 Application of simplification strategies in building

Simplifying LCA in the building life cycle has been attempted regularly since the end of the 2000s. Table 5 gives an overview of the categorisation of simplification strategies presented in Paper I. In this section, common applications of these simplification strategies in the building life cycle are presented. In line with the scope of this licentiate, some common practices are especially relevant for Swedish practitioners and multifamily residential buildings.

Exclusion-based simplification strategies are widely used in assessing the building life cycle. LCA can be simplified by restricting the inventory model to the product stage (A1-3) and operational energy use (B6) (Zabalza Bribián et al., 2009). From this basic model, the inventory model can be gradually extended, for example by adding the construction stage (A4-5), maintenance and replacement (B2, B4), and end-of-life processes (C1-4) (c.f. Liljenström et al., 2015). Furthermore, the LCA can be simplified by limiting the impact categories. It is common practice in building LCA to limit the assessment to GWP. A slightly more extensive assessment includes both $CO_{2\text{-eq}}$ emissions and Cumulative Energy Demand (CED) (Liljenström et al., 2015; Zabalza Bribián et al., 2009).

Table 5: Applications of simplifying strategies in building LCA

Simplifying logic	*Simplification strategies*	*Common practice in building LCA*	*Example reference*
Exclusion	Inventory model	Limit inventory model to product Stage A1-3 and operational energy use B6	Zabalza Bribián et al., 2009
	Impact categories	Limit impact categories to GWP, add cumulative energy demand	Zabalza Bribián et al., 2009
Data substitution	Bill of Resources	Estimate missing data in bill of resources Use energy simulation results for operational energy use	Soust-Verdaguer et al., 2016
	Emission data	Use generic data from a database, preferably adapted for regional electricity mix	Soust-Verdaguer et al., 2016
Expert judgement	Matrix LCA	Matrix LCA	Weinberg, 1998
Standardisation	Methodological standards	Follow EN15978, EN15804 Follow EeB guide, Boverkets guide	Lasvaux et al., 2014
	Standardised LCA tools	Use ENSLIC simplified method Use BM1.0 climate tool	Malmqvist et al., 2011
Automation	Computational LCA	Use parametric LCA to calculate many alternatives Use building LCA software like BM1.0 or OneClick LCA	Hollberg & Ruth, 2016
	Automated data integration	Collect bill of resources from a BIM model	Hollberg, Tschetwertak, Schneider, & Habert, 2018

Data-substitution is also a widely used simplifying logic in building LCA. It is common practice to estimate missing data in the bill of resources. Results from energy simulations required for energy declarations can be used to efficiently estimate operational energy use (Soust-Verdaguer, Llatas, & Garcia-Martinez, 2016). Similarly, it may be necessary to estimate the use of materials that are missing or poorly described. In selecting emission data, it is common practice to use generic data from available databases (Soust-Verdaguer et al., 2016). Well-known databases include EcoInvent and GaBi in Europe, and USLCI and Athena in North America. In Sweden, the BM1.0 LCA tool gives free access to generic climate data for the most commonly used building materials (Erlandsson, 2018a).

The combination of data-substitution and exclusion strategies are widely diffused in building LCA studies. It seems that the use of these simplification strategies has become the new normal. It is important to recognise, however, that these simplifications may reduce the completeness and accuracy of the inventory model. The use of GWP as a proxy indicator for environmental impact may lead burden shifting towards other impact categories which are not assessed.

Expert-based simplification strategies are less common in building LCA. An early example is a study of a manufacturing facility (Weinberg, 1998). Because of the extensive expertise needed to judge each category meaningfully, and the identified problems with LCA expertise in construction companies, it can be recommended to leave this approach aside for the time being.

Standardisation has contributed several simplification techniques for building LCA. Well-known methodological standards EN15879 and EN15804 structure parts of the LCA methodology for application in construction works (CEN, 2011) and EPDs of construction products (CEN, 2013). Additional guidance on building LCA has been developed in the EeB guide (Lasvaux et al., 2014). On a national level, the Swedish National Board of Housing, Building and Planning has released a guide for LCA of buildings (Boverket, 2019b). In the category of standardised LCA tools, the ENSLIC project developed an early example of a simple spread-sheet based tool (Malmqvist et al., 2011). In Sweden, the BM1.0 LCA tool provides also for a structured environment for climate calculation on building. Several more advanced LCA software tools are available but normally require a fee to use (Heincke, Dahlgren, Ek, & Beemsterboer, 2018).

Automation-based simplification strategies include computational LCA and automated data integration. Automating the computation of inventory and impact assessment results is an essential component of all spreadsheets and software tools. More ambitious computational approaches may use parametric models to calculate many different product alternatives (Hollberg & Ruth, 2016). While this may be useful in decision situations, parametric LCA is not recommended to a beginning analyst. The strategy of automated data integration is mainly applied in the compilation of a bill of resources in the inventory phase. Here LCA may benefit from the use of BIM models in building design to extract relevant building information (Hollberg et al., 2018).

These examples illustrate the existence of a wide variety of simplification strategies in building LCA. The existence these simplification strategies indicates that the methodological complexity of LCA does not legitimate an absence of LCA in residential buildings. There are, after all, many opportunities to make LCA studies simpler.

5 Discussion and outlook

The starting point in this licentiate is the claim that LCA is a complex methodology to apply. This claim is used often as an explanation to justify an ineffective use of LCA in the building life cycle. Both the ineffective use of LCA and the claim that LCA is complex have been examined in this licentiate. Chapters 2 and 3 present literature-based and empirical accounts of LCA practices. It is found that six sources of complexity affect the application of LCA in the building life cycle. While complexity should not be discounted, it is apparent that the types of complexity connected to the LCA methodology do not differ from those connected to the building life cycle. LCA may be difficult to understand, but this does not mean that it is more complex than a building project. Instead, LCA uncovers the complexity in a building project.

Besides complexity, several other causes that can explain the ineffective use of LCA in the building life cycle have been identified. Problems with demand, resources, data availability, and competence prevent a more effective use of LCA. Furthermore, the voluntary nature of LCA leaves it at a disadvantage compared with all the other requirements of a building project. The evidence presented in this licentiate suggests that these other problems are at least equally relevant explanations for the limited use of LCA in building.

A review of LCA simplification strategies in Chapter 4 identifies 11 different strategies for reducing the complexity of LCA, following five central simplifying logics. These strategies not only may make LCA easier to apply, they can also speed up the application of LCA. This is especially relevant in situations where time and other resources are scarce. The existence of a large variety of simplification strategies suggest that there are ample opportunities to reduce the complexity of LCA.

Hence, while the complexity of LCA should not be discounted completely, it is not a very credible explanation as a reason for the ineffective use of LCA in the building life cycle. Why then, does complexity get so much attention in the building LCA community?

5.1 Distinguishing complex from difficult to understand

A possible explanation may be derived from a colloquial expression of complexity as difficult to understand. It is useful to distinguish scientific complexity from LCA being difficult to understand. Even if LCA may not be more complex than other activities in the building life cycle, the actors involved may find it more difficult to understand. A simple reason for this is that most people and organisations lack experience with LCA and environmental knowledge. For LCA to become easier to understand, it is important to gain experience with the methodology.

The current conditions under which LCA is attempted in building companies appear far from ideal. LCA is applied sporadically, and mostly outside the context of a building project. In these conditions, it can be expected that people find LCA difficult to understand. The colloquial complexity attributed to LCA does not reside with the methodology or the aspiring practitioners. It is a consequence of the conditions within which LCA is attempted in building companies.

The distinction between complex and difficult to understand is relevant for an understanding of the ineffective use of LCA in buildings. Even if LCA is not more complex than cost accounting or project management, it is clearly a far less established discipline. This may make LCA appear more difficult to understand than strictly necessary. It can also explain why the perception of complexity persists despite the existence of many ways to simplify LCA.

It would, however, be beneficial for the academic LCA community to reflect critically on its own role. Compared to the extensive interest in methodology development, the LCA community has only sporadically considered the context in which LCA is used by companies in the product life cycle. In a situation with many possible explanations, many in the LCA community seem too eager to accept methodological inconsistencies as the main reason for an ineffective use of LCA.

Attention to methodological questions has strong historic roots in the LCA community. Ever since its first steps in 1970s, sharp criticism has held that LCA was not scientifically credible enough. LCA was accused of being a gun for hire, so to speak, to produce any result desired by the commissioner of the study. This has contributed to a strong set-back in the diffusion of LCA. With the renewed interest in LCA in the 1990s, the community has therefore prioritised the methodological and scientific credibility of LCA (Baumann & Tillman, 2004). Given the risk for further set-backs, it seems to have been a legitimate position to prioritise scientific credibility in the development of LCA. However, that position has also come with some important side effects.

A lopsided emphasis on the scientific character of LCA disregards that LCA is an assessment method at first. LCA passes evaluative judgement on the environmental status of product systems, with the explicit intention to act upon its recommendations. Restricting evaluative judgement to its scientific nature misses important social and value-oriented aspects (Guba & Lincoln, 1989). In LCA, these aspects are normally present in the goal and scope definition. The emphasis on scientific objectivity may disappoint users who experience more subjective elements that expected. Furthermore, it may explain a relative disregard for the practical context in which LCA is used to inform action (Freidberg, 2018; Lazarevic, 2018).

Life cycle *assessment* is not a positivist scientific approach focussed on a disinterested understanding of the environment and product systems. LCA is an assessment method aimed at environmental action in industry and society. Emphasising scientific credibility seems to have made the LCA community less attentive to the real-life conditions of LCA use in a company context. Hence, it may have contributed inadvertently to the acceptance of methodological answers to explain the ineffective use of LCA in building.

5.2 Towards a more effective use of LCA in the building life cycle

In 2022, the use of LCA-based climate declarations will be a state requirement in the Swedish building sector. In order to make more effective use of LCA in the building life cycle, it is not enough to merely apply LCA to calculate GWP of a finished building design. This does not bring about the changes in building environmental impacts that are so urgently needed. Neither does it enable an industry or organisation to effectively manage their product value-chain and resource flows. If the ambition is to make use of the full potential that LCA may hold for industry and ecology, it is necessary to move LCA into the heart of the building project.

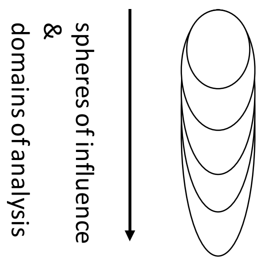
In building LCA, this implies a focus on the different stages in the building process, the professionals and stakeholders involved, the practices through which the building life cycle takes shape, and the organisational boundaries of the building project and building company. Within the life cycle community, the ambition to manage environmental burdens throughout the product life cycle is expressed in life cycle management (LCM) (Remmen, 2007). LCA is part of a portfolio of instruments that is used to promote environmental LCM in organisations (Nilsson-Lindén, Baumann, Rosén & Diedrich, 2018).

In the remainder of this doctorate project, the aim is to understand the ways in which LCA may contribute effectively to a more environmentally friendly building life cycle. Contrary to expectations voiced in some documents (e.g. Boverket, 2018), I do not expect this influence to be *certain.* Knowing about the environmental impacts is not the same as avoiding these impacts. On top of that, it is not even clear whether the information produced in a climate declaration contributes much to knowledge in the building life cycle. Table 6 shows some of the steps that a building LCA should achieve before it may have positively influenced the natural environment. Each step entails overcoming barriers and dealing with competing events. The more aspects in a building life cycle that LCA results are expected to influence, the more difficult these linkages become to analyse.

If LCA is to be used effectively to reduce climate impacts, then it would be beneficial to take a more explicit governance perspective to LCA in the building life cycle. Governance is a term that covers the efforts to purposefully influence people on behalf of others. The term governance is primarily used for attempts to influence and steer in a fragmented environment (Hoppe, 2011; Rose, 1999). It has been argued that governance in liberal democracies is justified from a discourse of truth and connects to an interest in numerical instruments

(Desrosières, 2002; Rose, 1999). LCA contributes to this discourse by aiming to present systematic and quantified environmental knowledge about a product life cycle. A governance perspective can help explain how and where LCA can influence the building life cycle.

Table 6: Spheres of influence in the building life cycle



LCA
LCA influences understanding
LCA influences behaviour
LCA influences building design
LCA influences building environmental performance
LCA influences natural environment

Adopting a governance approach may benefit from insight generated by actor network theory (ANT). This approach finds its basic premise in the equal treatment of both human and non-human elements of technology (Latour, 2005). Adopting what is referred to as a flat ontology, ANT may be used to give equal attention to different parts of the building life cycle. It places building technologies, resource and emission flows, and LCA knowledge on an equal setting with the people and activities in the building project. With the use of a flat ontology, the researcher's task becomes one of following the resource and material flows throughout the building life cycle, following the architects, engineers, and construction workers in their daily activities, and following the building through its different project stages. The ambition is to develop an empirically grounded understanding of the different ways in which LCA may influence the building life cycle and its environmental burdens.

The integration of LCA in the planning, design, and construction of residential buildings will be studied in detail through longitudinal ethnographic research at two building projects (Beemsterboer, Baumann, & Wallbaum, 2018). Observing key stakeholders in their day to day practices in the building project, in combination with conducting LCAs of the building design progress, can generate new insights into the ways in which LCA can influence the building life cycle.

5.3 Concluding remarks

This licentiate shows that methodological complexity is recognised extensively as a problem in academia and industry. It concludes that complexity is not a very credible reason for the ineffective use of LCA in the building life cycle. While LCA may be difficult to understand, this does not mean that LCA is more complex than the successful completion of a building project. This is especially true for those studies that limit the environmental scope to an assessment of global warming potential. There are important other reasons that explain the ineffective use of LCA, many of which are connected to the conditions under which LCA is attempted in the studied building companies. Furthermore, a wide variety of simplification strategies is available to simplify LCA. These strategies can be used to make LCAs easier and quicker to conduct. However, as LCA aims to uncover the complexity of a building project, it may be useful to not simplify too much.

References

Abel, E., & Elmroth, A. (2008). *Byggnaden som system*. Stockholm: Forskningsrådet Formas.

Adalberth, K. (1997). Energy use during the life cycle of single-unit dwellings: Examples. *Building and Environment, 32*(4), 321-329. doi:http://dx.doi.org/10.1016/S0360-1323(96)00069-8

Allacker, K., Souza, D. M. d., & Sala, S. (2014). Land use impact assessment in the construction sector: an analysis of LCIA models and case study application. *The International Journal of Life Cycle Assessment, 19*(11), 1799-1809. doi:10.1007/s11367-014-0781-7

Alvesson, M., & Sköldberg, K. (2009). *Reflexive methodology: New vistas for qualitative research (2nd ed)*. London: Sage.

Andersson, K., & Björkhagen, I. (2018). *Material Choices for a Fossil-Free preschool. An interview study on how materials are chosen, and a life cycle assessment of hemp insulation.* (Master thesis). Chalmers University of Technology, Gothenburg. (ACEX30-18-14)

Baumann, H. (1996). LCA use in Swedish industry. *The International Journal of Life Cycle Assessment, 1*(3), 122-126.

Baumann, H. (2012). *Using the life cycle approach for structuring organizational studies of product chains.* Paper presented at the Greening of Industry Network 2012 conference. Linköping, October 21-24.

Baumann, H., & Tillman, A. M. (2004). *The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application*. Lund: Studentliteratur.

Beemsterboer, S., Baumann, H., & Wallbaum, H. (2018). *Integrering av LCA i planering, utformning och konstruktion av bostäder*. Proposal granted by the Swedish National Board of Housing, Building and Planning (Boverket).

Berge, B. (2009). *The ecology of building materials* (2^{nd} edition 2015). New York: Routledge.

Berglund, A., & Cederbom, D. (2017). *Environmental impact from space efficient dwellings. Can space efficient multi-family dwellings be beneficial to reduce the environmental impact from housing.* (Masters thesis). Chalmers University of Technology, Gothenburg. (BOM-02-17-75)

Birgisdottir, H., Moncaster, A., Wiberg, A. H., Chae, C., Yokoyama, K., Balouktsi, M., . . . Malmqvist, T. (2017). IEA EBC annex 57 'evaluation of embodied energy and CO2eq for building construction'. *Energy and Buildings, 154*, 72-80. doi:https://doi.org/10.1016/j.enbuild.2017.08.030

Boverket. (2009). *Utvärdering av systemet med energideklarationer. Uppdrag nr 12 Uppföljning av energideklarationer enligt regleringsbrev för budgetåret 2009 avseende Boverket*. Karlskrona: Boverket.

Boverket. (2016). *Miljö- och klimatanpassade byggregler: Förstudie.* Karlskrona: Boverket.

Boverket. (2018). *Klimatdeklaration av byggnader. Föreslag på metod och regler.* Karlskrona: Boverket.

Boverket. (2019a). *Miljöindikatorer 2018 - en sammanställning av de texter som publicerats på boverket.se*. Karlskrona: Boverket.

Boverket. (2019b). Vägledning om LCA för byggnader. Karlskrona: Boverket.

Brand, S. (1994). *How buildings learn: what happens after they're built*. London: Phoenix.

Brandt, A., & Sonesson, H. (2017). *The environmental potential of hybrid load bearing systems - a life cycle assessment of a Skanska residential reference house.* (Master thesis). Chalmers University of Technology, Gothenburg. (BOMX02-2017-25)

Brundtland, G. H., Khalid, M., Agnelli, S., Al-Athel, S., & Chidzero, B. (1987). *Report of the World Commission on Environment and Development: Our common future*. New York: UN WCED.

Buyle, M., Braet, J., & Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews, 26*, 379-388. doi:https://doi.org/10.1016/j.rser.2013.05.001

CEN. (2011). EN 15978:2011 In *Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*. Brussels: European Committee for Standardization (CEN).

CEN. (2013). 15804:2012+A1:2013 In *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*. Brussels: European Committee for Standardization (CEN).

Christiansen, K. (1997). *Simplifying LCA: Just a Cut?: Final Report from the SETAC-Europe LCA Screening and Streamlining Working Group* (9056070061). Setac.

Churchman, C. W., & Churchman, C. W. (1971). *The design of inquiring systems: Basic concepts of systems and organization*: New York: Basic books.

Cole, R. J. (1998). Emerging trends in building environmental assessment methods. *Building Research & Information, 26*(1), 3-16. doi:10.1080/096132198370065

Curran, M. A., & Young, S. (1996). Report from the EPA conference on streamlining LCA. *International Journal of Life Cycle Assessment, 1*(1), 57-60. doi:10.1007/BF02978640

Desrosières, A. (2002). *The politics of large numbers: A history of statistical reasoning*: Cambridge: Harvard University Press.

Dubois, A., & Gadde, L.-E. (2002). The construction industry as a loosely coupled system: implications for productivity and innovation. *Construction Management and Economics, 20*(7), 621-631. doi:10.1080/01446190210163543

Erlandsson, M. (2018a). *Byggsektorns Miljöberäkningsverktyg BM1.0. Ett branschgemensamt verktyg*. Stockholm: IVL / E2B2.

Erlandsson, M. (2018b). *Datakvalitet för en LCA-beräkning av ett byggnadsverk - inklusive dokumentation av resurssammanställningen*. Stockholm: IVL / Smart Built Environment.

Erlandsson, M., Malmqvist, T., Francart, N., & Kellner, J. (2018). *Minskad klimatpåverkan från nybyggda flerbostadshus*. Stockholm: IVL / Sveriges Byggindustrier.

Erlandsson, M., & Pettersson, D. (2015). *Klimatpåverkan för byggnader med olika energiprestanda*. Stockholm: IVL.

Farahani, A. (2019). *A systematic approach to strategic maintwenance and renovation planning in multifamily buildings.* (PhD dissertation). Chalmers University of Technology, Gothenburg. (4592)

Fossilfritt Sverige. (2018). *Färdplan för fossilfri konkurrenskraft. Bygg- och anläggningssektorn*. Retrieved from Stockholm: http://fossilfritt-sverige.se/wp-content/uploads/2018/01/ ffs_bygg_anlggningssektorn181017.pdf

Freidberg, S. (2018). From behind the curtain: talking about values in LCA. *The International Journal of Life Cycle Assessment, 23*(7), 1410-1414. doi.org/10.1007/s11367-015-0879-6

Gibassier, D. (2017). From écobilan to LCA: The elite's institutional work in the creation of an environmental management accounting tool. *Critical Perspectives on Accounting, 42*, 36-58. doi.org/10.1016/j.cpa.2016.03.003

Gielen, D. (1997). Building materials and CO 2: Western European emission reduction strategies. Petten: ECN.

Glaumann, M., Malmqvist, T., Peuportier, B., Wetzel, C., Scarpellini, S., Zabalza, I., . . . Degiovanni, V. (2010). *Guidelines for LCA calculations in Early Design Phases. ENSLIC Building Deliverable*. Retrieved from http://kth.diva-portal.org/smash/get/ diva2:478408/FULLTEXT01.pdf

Gluch, P. (2005). *Building Green - Perspectives on Environmental Mangagement in Construction.* (PhD dissertation). Chalmers University of Technology, Gothenburg.

Gluch, P., Gustafsson, M., Thuvander, L., & Baumann, H. (2014). Charting corporate greening: environmental management trends in Sweden. *Building Research & Information, 42*(3), 318-329. doi.org/10.1080/09613218.2014.855873

Graedel, T. E. (1998). *Streamlined life-cycle assessment*. Upper Saddle River, NJ: Prentice Hall

Graedel, T. E., & Lifset, R. (2016). Industrial Ecology's First Decade. In R. Clift & A. Druckman (Eds.), *Taking Stock of Industrial Ecology* (pp. 3-20): Heidelberg: Springer.

Grant, M. J., & Booth, A. (2009). A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal, 26*(2), 91-108. doi.org/10.1111/j.1471-1842.2009.00848.x

Guba, E. G., & Lincoln, Y. S. (1989). *Fourth Generation Evaluation*. Newbury Park: Sage.

Guy, B., Shell, S., & Esherick, H. (2006). Design for deconstruction and materials reuse. *Proceedings of the CIB Task Group, 39*(4), 189-209.

Hansson, B., Olander, S., Landin, A., Aulin, R., & Persson, U. (2015). *Byggledning Projektering* (Vol. 1). Lund: Studentlitteratur AB.

Heincke, C., Dahlgren, L., Ek, K., & Beemsterboer, S. (2018). *Livscykelanalyser - vägledning vid val av verktyg*. Gothenburg: SBUF.

Hellweg, S., & Mila i Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science, 344*(6188), 1109-1113. doi:DOI: 10.1126/science.1248361

Henriksson, J., & Ulander, E. (2019). *It is all about the details. A life cycle assessment on a building project in Swden with focus on the level of details in the inventory data.* (Master thesis). Chalmers University of Technology, Gothenburg. (ACEX30-19-63)

Hillman, K. (2008). *Environmental Assessment and Strategic Technology Choice. The case of renewable transport fuels.* (PhD dissertation). Chalmers University of Technology, Göteborg.

Hollberg, A., & Ruth, J. (2016). LCA in architectural design—a parametric approach. *The International Journal of Life Cycle Assessment, 21*(7), 943-960. doi.org/10.1007/s11367-016-1065-1

Hollberg, A., Tschetwertak, J., Schneider, S., & Habert, G. (2018). Design-Integrated LCA Using Early BIM. In E. Benetto, K. Gericke, & M. Guiton (Eds.), *Designing Sustainable Technologies, Products and Policies: From Science to Innovation* (pp. 269-279). Cham: Springer.

Hoppe, R. (2011). *The governance of problems: Puzzling, powering and participation*. Bristol: Policy Press.

IPCC. (2013). *Climate change 2013: the physical science basis*. Cambridge: Cambridge UP.

ISO. (2006a). ISO 14040:2006 Environmental management - Life cycle assessment - Principles and Framework. Geneva: International Organization for Standardization (ISO).

ISO. (2006b). ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines. Geneva: International Organization for Standardization (ISO).

Klir, G. J. (1991). Systems movement. In *Facets of system science* (pp. 19-39). New York: Plenum press.

Koch, C., & Beemsterboer, S. (2017). Making an engine: performativities of building information standards. *Building Research & Information, 45*(6), 596-609. doi:10.1080/09613218.2017.1301745

Kono, J., Goto, Y., Ostermeyer, Y., Frischknecht, R., & Wallbaum, H. (2016). Factors for eco-efficiency improvement of thermal insulation materials. *Key Engineering Materials, 678*, 1-13. doi:10.4028/www.scientific.net/KEM.678.1

Kotaji, S., Schuurmans, A., & Edwards, S. (2003). *Life-Cycle Assessment in Building and Construction: A state-of-the-art report, 2003*: Brussels: Setac.

Larsson, M., Erlandsson, M., Malmqvist, T., & Kellner, J. (2016). *Byggandets klimatpåverkan-Livscykelberäkning av klimatpåverkan för ett nyproducerat energieffektivt flerbostadshus med massiv stomme av trä*. Stockholm: IVL / Sveriges Byggindustrier.

Lasvaux, S., Gantner, J., Wittstock, B., Bazzana, M., Schiopu, N., Saunders, T., . . . Fullana-i-Palmer, P. (2014). Achieving consistency in life cycle assessment practice within the European construction sector: the role of the EeBGuide InfoHub. *The International Journal of Life Cycle Assessment, 19*(11), 1783-1793. doi.org/10.1007/s11367-014-0786-2

Latour, B. (2005). *Reassembling the social: An introduction to actor-network-theory*. Oxford: Oxford UP.

Lazarevic, D. (2018). The legitimacy of life cycle assessment in the waste management sector. *The International Journal of Life Cycle Assessment, 23*(7), 1415-1428. doi:10.1007/s11367-015-0884-9.

Lewandowska, A., Noskowiak, A., Pajchrowski, G., & Zarebska, J. (2015). Between full LCA and energy certification methodology—a comparison of six methodological variants of buildings environmental assessment. *International Journal of Life Cycle Assessment, 20*(1), 9-22. doi:10.1007/s11367-014-0805-3

Liljekow, C., Rosén, S., & Tibäck, A. (2012). *Erfarenheter och Utblickar för användning av LCA. Hur kommer nya byggproduktförordningen CPR bilaga 1 att fungera i praktiken.* Malmö: SBUF.

Liljenström, C., Malmqvist, T., Erlandsson, M., Fredén, J., Adolfsson, I., Gustav, L., & Brogren, M. (2015). *Byggandets klimatpåvekan, Livscykelberäkning av klimatpåverkan och energianvändning för ett nyproducerat energieffektivt flerbostadshus i betong*. Stockholm: IVL / Sveriges Byggindustrier.

Lotteau, M., Loubet, P., Pousse, M., Dufrasnes, E., & Sonnemann, G. (2015). Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. *Building and Environment, 93*, 165-178. doi:https://doi.org/10.1016/j.buildenv.2015.06.029

Malmqvist, T., & Erlandsson, M. (2017). *LCA-baserade miljökrav i byggandet. Verktygslåda för livscykelanalys i byggandet*. Stockholm: E2B2.

Malmqvist, T., Glaumann, M., Scarpellini, S., Zabalza, I., Aranda, A., Llera, E., & Diaz, S. (2011). Life cycle assessment in buildings: The ENSLIC simplified method and guidelines. *Energy, 36*(4), 1900-1907. doi:10.1016/j.energy.2010.03.026

Meex, E., Knapen, E., & Verbeeck, G. (2016). *Analys of the material-related design decision process in Flemish architectural practice.* Paper presented at the Sustainable Built Environment (SBE) Regional Conference, Zurich, June 15-17.

Nägeli, C., Farahani, A., Österbring, M., Dalenbäck, J.-O., & Wallbaum, H. (2019). A service-life cycle approach to maintenance and energy retrofit planning for building portfolios. *Building and Environment*, 106212. doi.org/10.1016/j.buildenv.2019.106212

Nilsson-Lindén, H., Baumann, H., Rosén, M., & Diedrich, A. (2018). Organizing life cycle management in practice: challenges of a multinational manufacturing corporation. The International Journal of Life Cycle Assessment, 23(7), 1368-1382. doi:10.1007/s11367-014-0818-y

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. Construction and Building Materials, 23(1), 28-39. doi:https://doi.org/10.1016/j.conbuildmat.2007.11.012

Passivhus IG. (2019). Vad är ett passivhus? Retrieved from http://www.igpassivhus.se/passivhuset/vad-ar-ett-passivhus/

Peñaloza, D., Erlandsson, M., & Falk, A. (2016). Exploring the climate impact effects of increased use of bio-based materials in buildings. *Construction and Building Materials, 125*, 219-226. doi:https://doi.org/10.1016/j.conbuildmat.2016.08.041

Ponting, C. (2007). *A new green history of the world: the environment and the collapse of great civilizations*: New York: Random House.

Ramage, M., & Shipp, K. (2009). *Systems Thinkers*. London: Springer.

Ramesh, T., Prakash, R., & Shukla, K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings, 42*(10), 1592-1600. doi.org/10.1016/j.enbuild.2010.05.007

Regeringskansliet. (2019). *Uppdrag att förbereda införandet av krav på redovisning av en klimatdeklaration vid uppförande av byggnader*. (Fi2+19/02439/BB). Stockholm.

Remmen, A. (2007). *Life cycle management: a business guide to sustainability*. UNEP/Earthprint.

Rittel, H. W. J., & Webber, M. M. (1973). Dillemas in a General Theory of Planning. *Policy Sciences, 4*(2), 155-169. doi.org/10.1007/BF0140573

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., . . . Schellnhuber, H. J. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society, 14*(2). 10.1038/461472a

Rose, N. (1999). *Powers of freedom: Reframing political thought*: Cambridge: Cambridge UP.

Rossi, B., Marique, A.-F., Glaumann, M., & Reiter, S. (2012). Life-cycle assessment of residential buildings in three different European locations, basic tool. *Building and Environment, 51*, 395-401. doi:http://dx.doi.org/10.1016/j.buildenv.2011.11.017

Sandén, B. (2004). Technology Path Assessment for Sustainable Technology Development. *Innovation: Management, Policy & Practice, 6*(2), 316-330. doi:10.5172/impp.2004.6.2.316

Sandén, B., & Karlström, M. (2007). Positive and negative feedback in consequential life-cycle assessment. *Journal of Cleaner Production, 15*(15), 1469-1481. doi:http://dx.doi.org/10.1016/j.jclepro.2006.03.005

Simon, H. A. (1962). The architexture of complexity. *Proceedings of the American Philosophical Society, 106(6)*, 467-482. www.jstor.org/stable/985254.

Soust-Verdaguer, B., Llatas, C., & Garcia-Martinez, A. (2016). Simplification in life cycle assessment of single-family houses: A review of recent developments. *Building and Environment, 103*, 215-227. doi:10.1016/j.buildenv.2016.04.014

Star, S. L. (1983). Simplification in Scientific Work: An Example from Neuroscience Research. *Social Studies of Science, 13*(2), 205-228. doi:10.1177/030631283013002002

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., . . . De Wit, C. A. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science, 347*(6223), 1259855. DOI: 10.1126/science.1259855

Svensk byggtjänst. (2019). BSAB. Retrieved from https://byggtjanst.se/tjanster/bsab/

Sveriges Byggindustrier. (2018). 30 största byggföretagen efter omsättning i Sverige. Retrieved from https://www.sverigesbyggindustrier.se/UserFiles/pdf/30_storsta_.pdf

Säynäjoki, A., Heinonen, J., Junnila, S., & Horvath, A. (2017). Can life-cycle assessment produce reliable policy guidelines in the building sector? *Environmental Research Letters, 12*(1), 013001. 013001doi:10.1088/1748-9326/aa54ee

Todd, J. A., & Curran, M. A. (1999). *Streamlined life-cycle assessment: a final report from the SETAC North America streamlined LCA workgroup*. SETAC.

Trafikverket. (2015). *Klimatkalkyl- infrastrukturhållningens energianvändning och klimatpåverkan i ett livscykelperspektiv*. Trafikverket.

Weinberg, L. (1998). *Development of a streamlined, environmental life-cycle analysis matrix for facilities.* Paper presented at the IEEE International Symposium on Electronics and the Environment, Oak Brook, May 6. 10.1109/ISEE.1998.675032

Weitz, K. A., Todd, J. A., Curran, M. A., & Malkin, M. J. (1996). Streamlining life cycle assessment: Considerations and a report on the state of practice. *International Journal of Life Cycle Assessment, 1*(2), 79-85. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-0002700578&partnerID=40&md5=f9b34729fc8422650affa6605fb30b02

Winch, G. (2010). Managing construction projects: an information processing approach. In. Chichester: Wiley-Blackwell.

Wolfswinkel, J. F., Furtmueller, E., & Wilderom, C. P. (2013). Using grounded theory as a method for rigorously reviewing literature. *European journal of information systems, 22*(1), 45-55. doi.org/10.1057/ejis.2011.51

Ylmén, P. (2017). *Environmental and Cost Assessments of Buildings. The inportance of secondary effects.* (Licentiate thesis). LTH, Lund. (TVBH-3066)

Zabalza Bribián, I., Aranda Usón, A., & Scarpellini, S. (2009). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment, 44*(12), 2510-2520. doi:10.1016/j.buildenv.2009.05.001